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PAHOEHOE, AA, AND BLOCK LAVA*

GORDON A. MACDONALD

ABSTRACT. Pahoehoe is characterized by a smooth, billowy, or ropy surface, and spheroidal vesicles. Aa is characterized by a fragmental and spinose surface, and irregularly shaped vesicles. Block lava differs from aa in greater regularity of the shapes of the fragments in the breccia phase, and less spinose surfaces. Beneath the fragmental tops of aa and block lava flows is a nearly continuous nonfragmental layer. Pahoehoe is a more primitive form, richer in gas, than aa. The three types of flows form a continuous intergradational series.

The formation of aa instead of pahoehoe is largely the result of greater viscosity resulting from lower temperature, smaller gas content, and more advanced crystallization. The typical spinosity of aa results from continued flow after loss of gas and crystallization have imparted a definite granularity to the lava. Fragmentation of the surface of the flow occurs at a stage determined by both viscosity and rate of flow. In more salic lavas the higher viscosity results in fragmentation at a lesser degree of crystallinity than in basaltic lavas, and the fragments of a block lava flow are therefore less granular and spinose than those of typical aa.

INTRODUCTION

THE purpose of this paper is threefold: to describe the structural features of recent lava flows as an aid to the recognition of similar flows in old geologic terranes; to point out certain fundamental relationships between pahoehoe, aa, and block lava, and set forth in so far as possible the apparent reasons for the formation of one type or another; and to attempt to correct certain persistent errors concerning the genetic relationships and structure of aa and pahoehoe.

Pahoehoe may be defined as the type of lava that in solidified form is characterized by a smooth, billowy, or ropy surface, and *aa* as the type characterized by a rough, jagged, spinose, and generally clinkery surface. To the ancient Hawaiians the terms had no further connotation, and the original definitions (Dutton, 1884, p. 95) implied nothing as to either internal

* Publication authorized by the Director, U. S. Geological Survey.

structure or mode of origin. It is now recognized, however, that not only the surfaces but also in general the internal structures of the two types of lava are distinctly different. The internal structures, as revealed in cross section, usually are much more useful than the surface characteristics in the recognition of the different types of flow in old terranes. In this paper the terms aa and pahoehoe are used to designate the entire flow, and not only the flow surface. Primarily, the terms refer to the partly or completely solidified flows, though commonly the surfaces of the molten feeding rivers also are sufficiently distinct in appearance to make possible their recognition as one type or the other.

Although pahoehoe and aa are very distinct in their characteristic development, there is complete intergradation between the two forms. Examples occasionally are found in which the characteristics are intermediate, or in which some characteristics belong typically to one form and others to the other form. This fact of intergradation between the two forms is important in considering their origin.

Block lava resembles aa in its general appearance, but is less spinose and the fragments are less irregular in form.

Since their introduction to geologic literature by Dutton (1884), the Hawaiian terms pahoehoe and aa have come into common use the world over. Basic volcanoes everywhere produce lavas which are closely similar in forms to the aa and pahoehoe of Hawaii. In general the recognition of the two types in other regions is quite accurate and consistent. However, there appear to be some confusion and misunderstanding as to their genetic relationships and structure, not only among geologists, but among volcanologists as well. During conversations with geologists interested in volcanic rocks it has become apparent to the writer that many of them are unaware of the general presence beneath the fragmental tops and margins of aa and block lava flows of a nearly continuous layer of nonfragmental material. Also, several leading volcanologists have expressed the belief that live aa lava contains more gas than does pahoehoe, and the statement is gradually finding its way into geologic literature as fact. Actually, the observed relationships and internal features appear to indicate conclusively that the opposite is true. Admittedly the evidence is largely from Hawaii, but the flow types are so closely similar, if not identical, all over the

earth that there is no reason to suppose the relationships are different in other regions.

Block lava is commoner than either aa or pahoehoe in the tectonic belts of the continents, but it appears to be only poorly understood by many geologists. Few geologists have had the experience of working with flows in regions of recent or present volcanism. Furthermore, workers in regions of fresh flows commonly either have not investigated the internal structures of the flows, or have not described them carefully in their published reports. Better knowledge of these structures will aid greatly in the interpretation of ancient volcanic rocks. It appears very probable that some of the breccias in old terranes which have been interpreted as pyroclastic are actually the fragmental portions of lava flows.

Recent pahoehoe and aa flows exhibit a great many structures, especially minor ones, which are seldom seen in ancient flows and which are not particularly germane to any of the purposes of this paper. These are touched upon herein only very briefly or not at all. Readers interested in greater detail of this sort are referred to a longer paper now in preparation (Wentworth and Macdonald).

The writer wishes to thank Doak C. Cox, geologist for the Hawaiian Sugar Planters' Association Experiment Station, Charles M. Gilbert, of the Department of Geological Sciences of the University of California, Ruth C. Macdonald, and W. H. Mathews for their careful reading and criticism of this paper. R. H. Finch, R. E. Wilcox, and H. A. Powers, of the U. S. Geological Survey, have been especially helpful in their criticism of the manuscript and discussion of many of the subjects covered therein. Much of the material has been discussed also with Hisashi Kuno, of the University of Tokyo, whose extensive knowledge of lava flows in Japan has been of great aid.

DESCRIPTION OF LAVA TYPES

Pahoehoe.—The surface of large pahoehoe flows is relatively smooth, with broad billows or hummocks, and locally rolls (plate 1, fig. 1). Small areas of ropy or corded surface are common, although not nearly as general as one would be led to understand from some textbooks.

The two principal characteristics of the internal structure of pahoehoe are the presence of lava tubes, either open or filled,

and the smooth spheroidal shapes of the vesicles. After the initial burst of liquid lava the top of the flow becomes crusted over and the advance of the lava is almost entirely internal, through the resulting lava tubes. Major rivers may remain open near the vents, but even they become roofed over, with the exception of occasional small openings or "windows," within a mile or two of the vents. In mature flows the major feeding rivers commonly are enclosed in tubes almost continuously from the vent to the actively advancing flow margin.

There are two principal modes of advance of pahoehoe flows. One is exhibited by pahoehoe flows of high mobility and generally relatively small size. In it the entire front advances essentially as a unit, with a rolling motion. The upper part of the sheet of liquid moves forward more rapidly than the lower part, and at the front of the flow is rolled under and buried by the lava coming after it. The other and commoner mode of advance is observed in flows of moderate to low mobility. In these each large tube divides into many smaller ones, each of which feeds a lobe of lava at the moving flow front. The entire front advances by successive protrusion of one small bulbous toe after another (plate 1, fig. 1). Most toes advance only a few feet before they chill to immobility, after which the skin of the flow front ruptures at some other point and another toe is sent out. Many toes advance in essentially the same manner as the highly mobile pahoehoe flow-front described above. Others extend themselves by a process of inflation, the skin remaining unbroken, or if broken, quickly sealed again by lava squeezed from within. The front is gradually built up by the accumulation of a heap of these toes, generally 1 to 3 feet in diameter, lying alongside and on top of each other and closely molded to each other. A few of the central tubes which fed the toes are more persistent, continue to function as feeding tubes, and even become enlarged by melting and stoping away of their walls and roofs to form the major supply channels as the flow advances down the mountainside.

Some very hot pahoehoe streams close to the vents during Mauna Loa eruptions are almost wholly uncrusted. Commonly, however, ropy crusts form on them momentarily, only to be torn apart and floated downstream as dark rafts on an incandescent bubbling liquid surface. Thus the river pouring along the erupting fissure during the 1950 eruption had a bright

orange surface agitated by lava fountains exploding through the river and with only scattered flecks of darker crust. Yet the crusts which were present showed the characteristic features of pahoehoe surfaces, and where overflows of liquid rolled over the banks typical ropy pahoehoe was formed. The surface of the lava river at the highway, 11 miles from the vents, appeared much like that at the vents except for a darker color resulting from lower temperature. But at the highway overflows formed aa, not pahoehoe, and fragments of crust on the river were aa.

Thin pahoehoe flows, and the upper part of thick flows, are characterized by very abundant vesicles. As was early noted by S. E. Bishop (cited by Hitchcock, 1909, p. 282), the vesicles typically are spherical or spheroidal, or composed of clusters of slightly to moderately distorted spheroids. The outlines of the vesicles are smooth regular curves. Many pahoehoe flows contain more than 20 per cent of these spheroidal vesicles, and it is not uncommon to find pahoehoe containing more than 50 per cent vesicles (Daly, 1911, p. 77). Some flows, especially in the summit region of Mauna Loa, are so rich in gas that they develop a surficial layer of exceedingly vesicular pumice (Finch, Powers, and Macdonald, 1948).

A heap of pahoehoe toes belonging to several successive flow units may appear in transverse cross section somewhat like pillow lava (plate 1, fig. 2), using the term "pillow lava" in the more useful restricted sense employed by Stearns (1938) and McKinstry (1939). It does not, however, have the same genetical interpretation as pillow lava, and its misinterpretation as such may lead to erroneous deductions regarding the geologic structure or history of an area. If they are well exposed, true pillow lavas can generally be distinguished without difficulty from pahoehoe toes. In general, in cross section each pillow gives an impression of radial structure, whereas each toe gives an impression of concentric structure (plate 1, fig. 2, and plate 2, fig. 1). When the forms are exposed in three dimensions it can be seen that the toes are commonly much more elongate than the pillows. The major axis of a pillow is seldom more than three or four times as long as the shorter axes, whereas a pahoehoe toe may exhibit a length along the principal axis of flowage several times greater than its cross-sectional dimensions. Three-dimensional exposures are comparatively rare, however. The following table lists some of the features useful in distin-

guishing two-dimensional cross sections of pahoehoe toes from those of pillows.

As pointed out by Stark (1939), the usage of the term "pillow lava" has in the past been exceedingly vague. It appears to the writer that the usefulness of the term can be much increased by restricting it to the forms herein termed pillows, as advocated by Stearns and McKinstry, the forms being distinct morphologically from pahoehoe tube structures as well as commonly having different environmental significance. The general term "ellipsoidal lavas" may then be used for any forms showing ellipsoidal cross sections, including both true pillows and pahoehoe toes.

Pahoehoe toes	*Pillow lavas*
Glassy shell commonly poorly developed.	Glassy shell generally well developed.
Commonly moderately to highly vesicular or amygdaloidal.	Commonly only moderately vesicular to poorly vesicular or amygdaloidal.
Vesicles commonly elongated tangentially or not at all.	Vesicles commonly elongated radially, especially near the edge.
Tube structures very common, resulting in axial cavities or forms resulting from the partial or complete filling of axial cavities.	Tube structures rare.
Radial joints generally poorly developed or absent.	Radial joints commonly well developed and conspicuous in cross section.
Interstitial spaces absent, or where present, open or filled with secondary minerals deposited by circulating water.	Interstitial spaces commonly filled with fine glassy debris or its alteration products, or with sedimentary material squeezed up from underlying bed or settled in from above.

Most pahoehoe flows are covered with a thin glassy skin (Powers, Ripperton, and Goto, 1932, p. 6). The skin commonly is a mere film, but in places it attains a thickness of an inch or even more. At least in some instances it appears probable that such exceptionally thick glassy skins have resulted from unusually rapid surface quenching, as by heavy rains (Finch, R. H., personal communication). While a pahoehoe toe is active the skin remains tough and flexible. It is so resistant to rupture that one can jump on the top of a small toe and cause the internal liquid to squirt out the end without breaking the skin on the top.

The skin commonly confines just below it a layer of gas bubbles risen from the underlying fluid. Most commonly the skin overlying the vesicle layer is less than a millimeter thick, and with weathering it soon flakes off. Occasionally the skin is puffed up as a distinct blister, as much as 3 or 4 feet across and a foot or two high, by the pressure of the accumulated gas. Close to some vents, especially on the upper slopes of Mauna Loa, there is an abundant development of so-called shelly pahoehoe. This consists of a mass of hollow toes and tubes covered by vesicular crust from 1 to 3 or 4 inches thick. The central cavities range from a foot to 3 feet or more in diameter. A few of the hollow tubes may have formed by draining away of the interior liquid, but many of the tubes and most of the toes along the edge of the flow could not have been formed in that manner, since there is no place for the liquid to have gone. These must have been blown up like balloons by the liberated gas.

Commonly the crust of an active pahoehoe flow remains sufficiently plastic to be dragged into twisted ropy forms and festooned folds by the movement of the fluid lava beneath. In most instances the curved ropes and festoons are convex in a downstream direction. However, local irregularities of flow may result in the festoon being convex upstream, and consequently this feature must be used with caution in an attempt to determine the direction of flowage from limited exposures in an old terrane.

During the brief interval before the flow crusts over, gas is liberated abundantly all over its surface. Many of the myriads of escaping gas bubbles drag behind them filaments of the viscous liquid lava. The filaments quickly solidify. In some instances they form sharp upright spines a millimeter or two high, but more commonly they bend largely or completely over before they become immobile and form an intricate lacy mass of threads on the flow surface. All these features, like the high vesicularity, point to high gas content in the typical liquid pahoehoe.

On some pahoehoe flows the crust has been fractured and broken up, and the surface of the flow consists of innumerable slabs tilted on edge, sometimes arranged in a fairly regular imbricated fashion, but more commonly lacking any regular arrangement (plate 2, fig. 2). This type of flow has been called slab lava by Jones (1943). The slabs are generally 2 to 6

inches thick and 1 to 4 or 5 feet across. Each shows one smooth or ropy surface, which once comprised the upper surface of the flow, and one rougher, more spinose surface which was formerly the under surface of the crust. Although the general aspect of the fragmental top resembles aa, each fragment is clearly pahoehoe. It is not uncommon, however, to find in this type of flow some development of spinosity and granularity indicating gradation toward aa, and in some slab lava a small amount of true aa clinker can be found associated with the slabs of pahoehoe crust. In some examples the fragmentation of the pahoehoe surface appears clearly to have been the result of increase of viscosity, accompanied by a transformation to aa, in the moving fluid beneath the crust.

Aa.—Aa lava is characterized by an exceedingly rough, jagged, or spinose surface (plate 3, fig. 1). Most of the surface is covered with loose fragmental material known as "clinker" or "flow breccia." The surficial clinker layer ranges in thickness from a few inches to several feet. Each of the fragments of clinker is exceedingly rough, irregular, and spiny. The general character defies verbal description, and an adequate idea of it is best conveyed by photograph (plate 3, fig. 1). Not all of the jagged surface material of the flow is loose clinker. Jaggar (1930, p. 3) has pointed out that many of the spinose boulder-like masses are rigidly connected with the solid central mass of the flow (plate 3, fig. 2). These apparently develop by a process of "sprouting" as the flow congeals. It appears probable that many of the loose fragments of clinker are formed by detachment of these spinose sprouts during movement of the flow, and somewhat modified in shape by attrition.

The clinker phase of the flow consists of fragments of all sizes from the maximum to fine dust. In many flows the maximum size of the clinker fragments is about 5 or 6 inches, but in some it is as much as 2 or 3 feet. In all flows there are a few scattered fragments larger than the general maximum. Commonly, however, there is a fairly definite upper limit of size with a large proportion of the fragments approaching it, and as noted by Krauskopf (1948, p. 1278) individual flows may be characterized more or less throughout their extent by coarse clinker or fine clinker. This has made it possible for Jones (1943) to classify flows as fine aa, medium aa, or coarse aa. Many of the fragments show evidence of some rounding by

Fig. 1. Pahoehoe of the 1919 lava flow on the floor of Kilauea Caldera. Note the smooth billowy surface, and the congealed toes along the edge of the upper flow unit. The latter is 12 to 18 inches thick.

Fig. 2. Ellipsoidal cross sections of pahoehoe toes, in the sea cliff near Waialua, island of Molokai, Hawaii. Note the distinct concentric arrangement of flow banding and vesicles, and the absence of radial structure. The toe in the center is 2 feet across.

Fig. 1. Pillow lavas at the Menehune Ditch, Waimea River, island of Kauai, Hawaii. Note the radial structure. Photo by D. A. Davis.

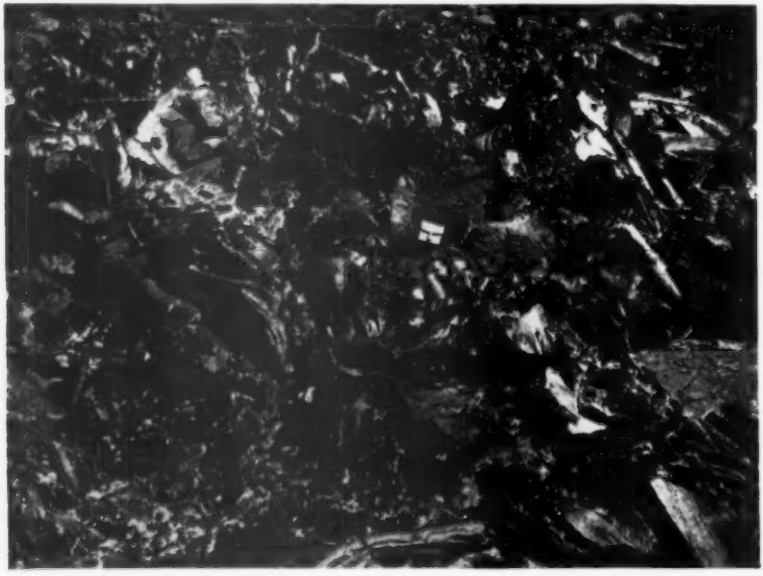

Fig. 2. Slab pahoehoe, on floor of Kilauea Caldera, Hawaii. Each of the fragments is a sheet of pahoehoe crust. The camera case is 6 inches across.

mutual abrasion during movement of the flow. This same abrasion creates fine sand and dust which lie in the interstices between the larger fragments. Dust generally comprises only a very small proportion of the material, not nearly enough to form a continuous matrix for the larger fragments. In new flows the clinker phase is open-structured and very permeable to ground water, although in older flows, especially where they have been deeply buried, there is a great reduction in pore space owing to compaction and deposition of secondary materials. Commonly, even in new flows, below the surface the clinker fragments are stuck firmly together, apparently by adherence of still slightly plastic surfaces soon after movement of the flow stopped. This may be termed *welded clinker*, or *welded flow breccia*.

The fragmental phase of an aa flow does not closely resemble a pyroclastic breccia. The clinker fragments are quite distinctive in form, although difficult to describe, and differ in appearance from fragments of cinder or scoria. The principal differences are the denseness of the fragments and their spinosity. The breccia phase of some block lava flows (discussed later) rather closely resemble certain pyroclastic breccias, particularly in small exposures. In either aa or block lava flows gradation of the breccia into the massive phase serves to distinguish the breccia from a pyroclastic deposit. Also, the flow breccias are essentially monolithologic, fragments of rock types other than that which constitutes the flow being exceedingly rare. Pyroclastic breccias may also be essentially monolithologic, but admixture of other rock types is very much commoner than in flow breccias. Sorting, and bedding other than the general arrangement of phases in the flow and the succession of one flow on another are practically absent in flow breccias, and the presence of sorting or small-scale bedding may be taken as a criterion of pyroclastic origin.

Besides the clinker, there are present in the fragmental tops of many aa flows *accretionary lava balls*, formed by the rolling up of viscous lava around some solid fragment as a core (Macdonald, 1943, pp. 253-254). These balls range from a few inches to 15 or 20 feet in diameter. Their surfaces are for the most part rough and spiny, or even clinkery, although portions of the surface may be fairly smooth. On some flows they are abundant, but on others they are rare.

Typically, the upper clinker layer of an aa flow is underlain by, and grades into, a central massive layer (Macdonald, 1945). Only rarely and very locally is the massive layer lacking. Many flows also have a layer of clinker at the bottom, but that is commonly thinner and less persistent than the upper clinker layer (plate 4, fig. 1). The percentage of clinker in the flow commonly ranges from about 15 to 65 per cent, and averages less than 50 per cent.

In connection with the later discussion of origin of aa, it is important to note that the "sprouts" sometimes develop on extensive aa surfaces on which the crust is essentially continuous and loose clinker is nearly or entirely absent. At places of this sort the sprouts range in height from a quarter of an inch or less to 6 or 8 inches. It is possible that a few of them form by squeezing up through a dielike aperture in the flow crust, like the larger spines which are known to form in that way on the summits of many viscous domes (tholoids) and some thick viscous flows. Most, however, are so exceedingly irregular in form in all directions that they could hardly have formed in that way. Finch (personal communication) observed the formation of these spinose sprouts on a clinker-free aa surface during the 1920 eruption of Kilauea. He states that they seemed to grow almost like plants, and that there was no pulling apart of the crust involved.

Tongues of highly viscous lava of the sort termed "toothpaste lava" by some investigators (Bullard, 1947, p. 444; Einarsson, 1949, p. 31) may be squeezed out through openings in the flow crust, especially at and near the lower end of the flow. They generally show grooving and chatter-marks owing to friction against the sides of the opening. Commonly their surfaces are covered with characteristic small aa sprouts. Occasionally these "toothpaste" tongues are squeezed up through fractures in the flow top. They may be isolated or in groups, and rarely they may cover a fairly large area. Thus in the central part of a prehistoric aa flow near the southern coast of the island of Hawaii, between Punaluu and Kawaa, a series of slightly recurved grooved "toothpaste" squeeze-ups (Nichols, 1939), appearing almost like a series of breaking waves 2 to 4 feet high, occupies an area about 100 feet wide and 200 feet long.

The massive phase of aa is on the average distinctly less vesicular than pahoehoe, although there is great variation in the vesicularity of both types and it is possible to find many specimens of aa which are more vesicular than many specimens of pahoehoe. The vesicularity of aa may reach as much as 50 per cent, but it is generally less than 30 per cent. Typically the vesicles of aa (and block lava) are markedly irregular and distorted, and commonly they are much stretched in the direction of flowage. The contrast in vesicle shape between typical aa and typical pahoehoe is shown in plate 4, figure 2. Some exceptions exist, and gradational samples difficult to assign with certainty to either type are fairly common, but the general distinction between the shapes of aa and pahoehoe vesicles is quite marked and is a useful criterion for distinguishing the two types of lava in hand specimen or in cross sections of old flows in the field.

A typical active flow of aa consists of a main lava river, which flows in an open channel seldom more than 20 to 30 feet wide, bordered on each side by fields of clinkery aa as much as half a mile in width. The fluid lava of the river spreads out at the end of the flow to form the active front, and it also retains a close relationship with the central pasty layer which underlies the clinkery top in the marginal portions of the flow. On either side of the lava river, and particularly at the advancing front of the flow, the pasty central layer of the flow pushes outward. The marginal fields may continue to move slowly throughout the life of the flow, fed by the pasty central layer which in turn is fed from the main river. Surges of liquid lava in the main river may be accompanied by a slight swelling up of the marginal clinker fields, which may otherwise appear motionless (Finch and Macdonald, 1950, p. 8).

Generally aa flows are more viscous than pahoehoe flows, and advance much less rapidly than pahoehoe flows on the same slope. Commonly the most active part of the front advances only a few hundreds of feet to a mile or two a day. There are some exceptions, however. Thus the aa flows of the 1950 eruption on the western slope of Mauna Loa advanced at a rate of 1 to 2 miles an hour in the lower part of their courses (Finch and Macdonald, 1950, pp. 3-6). This high speed resulted largely from the steepness of the terrane, but partly also from lower than normal viscosity for an aa flow. The speed of advance of

the flow front is to be distinguished from the speed of flow of the lava in the upper portion of the main feeding river, which may locally reach as much as 30 miles an hour.

The advance of a typical aa flow front takes place in the following manner: The black or dark reddish brown clinkery front of the flow may appear temporarily as a steep, relatively immobile bank. Its liveness is shown only by moderate fume liberation, the typical hot iron odor, incessant grating and cracking of surficial rock resulting from cooling and slight shifting, an occasional boulder tumbling down the flow front, and especially at night by innumerable glaring red spots showing through the clinker cover from the deeper parts of the flow. During such times radiant heat may be so low that it is possible to walk directly up to the flow front.

Gradually the flow front steepens and bulges, sometimes imperceptibly but at other times at an easily observable rate. Movement is greater near the top, resulting in a tendency for the top to overhang the lower portion of the front. Eventually the bulging results in instability at some point on the flow front, and a slab of dark clinkery rock peels off, breaks into fragments, and tumbles to the foot of the bank with a sound like the clinking of breaking crockery (plate 5, fig. 1). A talus bank of fragmental material forms against the base of the flow front. Attrition of the rolling fragments often results in a rising cloud of dust. At the point where the slab of rock broke away there is revealed a glowing hot face of the pasty lava in the interior of the flow, and radiant heat is suddenly greatly increased, making it decidedly uncomfortable to remain close to the flow margin. The falling and fracturing block also is generally incandescent inside. The exposed glowing paste is quickly chilled to a dark clinkery flow front, which again remains relatively immobile until bulging makes it unstable. In the meantime, the same process is going on at other points on the flow front.

In detail, the separation of the large fragment commonly is preceded and accompanied by granulation of the immediately adjacent material, producing streamlets of incandescent sand and pebbles down the flow front. In its final separation, the large fragment commonly tilts forward as the fracture behind it opens downward, until it finally breaks free and tumbles down the embankment. More rarely the block separates by gliding forward apparently on a forward-sloping fracture beneath.

The flow tends to advance over a layer of its own debris, formed by collapse of the repeatedly bulging front. The spasms of bulging may occur every few seconds, or at intervals of several minutes, depending on the activity of the flow. In very rapidly advancing flows it is essentially continuous, and the rolling of blocks down the flow front to its base, to be overridden by the advancing flow, gives somewhat the same impression as the forward rolling motion of tractor or tank treads.

Occasionally, particularly in thin flows, the pasty layer may move forward with little or no collapse of the front, chilling to form a spinose clinkery top, but developing little or no basal clinker. The gliding forward of the flow over an irregular surface may cause grooving of the lower side of the pasty layer.

The difference between aa and pahoehoe is sometimes not apparent in the appearance of the molten lava of the main feeding channel. The surface of the main river of an active aa flow may appear very much like that of an uncrusted river near the vents which is making pahoehoe along its edges, or even that of a large pahoehoe river viewed through a window in the roof of a tube. However, less active rivers commonly show evanescent skins of the type of material being formed at their margins. Thus a pahoehoe river commonly develops thin skins of ropy pahoehoe, and an aa river shows a tendency for the development of a clinkery and spinose surface.

There are some instances in Hawaii of aa being erupted directly from the vent. Dikes, many of them probably the feeders of surface flows, occasionally show the vesicle forms of typical aa, and rarely even the fragmental structure of aa (Stearns, 1940, pp. 39-40). Generally, however, the lava issues from the vent as pahoehoe. There are some examples, like the Mauna Loa flow of 1881, in which the lava remained pahoehoe flowing in tubes all the way to the terminus of the flow, many miles downslope. More commonly, however, the lava changes from pahoehoe to aa within a few miles of the vent. It is very common, in fact it is the normal sequence of events for a flow to change from pahoehoe to aa during its course. Often the last lava to move through a large pahoehoe tube is aa, which consolidates to form a typical spinose aa surface on the floor of the tube.

In contrast, the reverse change, from aa to pahoehoe, is unknown. A few examples which on first sight appeared to represent changes of aa into pahoehoe on further examination

appear almost certainly to have resulted from a pahoehoe flow burrowing under a slightly older flow of aa and emerging at its snout. The statement has been made in some older literature on Hawaiian volcanoes that early flows of aa changed to pahoehoe as the eruption progressed. Apparently, however, what actually happened was that later pahoehoe flows advanced over and beyond earlier aa flows. Although that is not the most common sequence, it has been observed during several eruptions. It is not at all the same as a change of the same flow from aa to pahoehoe. The latter has never been substantiated.

Block lava.—True aa appears to be confined in its occurrence to basaltic lavas (including basaltic andesites and the ultramafic feldspathoidal lavas). The more salic lavas characteristically exhibit a form much like aa, but distinct from it in the absence of the spinose character typical of aa. Finch (1933) has proposed that this type be termed *block lava*, thus restricting a term used by many German and Dutch writers for partly fragmental lavas in general, including aa. Block lava is distinguished from true aa by the fact that the individual fragments are relatively smooth polyhedral blocks bounded by dihedral angles, lacking the exceedingly rough and spinose character of typical aa (plate 5, fig. 2). In other words, in block lava the fragments are more regular in shape and tend to have somewhat smoother faces than do those in aa.

It is common to find much variation in the smoothness of the faces of the blocks. On a single block some faces may be smooth, but others spinose. In typical block lava, however, the spinosity seldom even locally equals that characteristic of aa. To be sure, some flows are difficult to classify as one form or the other. I have never observed a gradation from aa to block lava within a single flow, but in separate flows every gradation in form of fragments and spinosity from typical aa to typical block lava can be found.

The overall structure of block lava is essentially identical to that of aa. Commonly the flows are thicker and slower moving than those of aa. Typical aa seldom attains a thickness as great as 50 feet except where it is ponded, and most flows are less than 30 feet thick. In contrast, block lava flows quite commonly exceed 50 feet in thickness. Both the fragmental and massive parts of block lava flows generally contain a larger proportion of glass than do the corresponding portions of aa flows. Also,

the fragmental material typically makes up a greater proportion of the flow, and more commonly than in aa constitutes the whole thickness of the flow. However, even in block lava the absence of the central massive layer is a purely local condition. In most places the massive phase is present, overlain and generally underlain by breccia. In exposures that are continuous for several hundred feet the massive phase generally can be seen near the base of the flow, as a continuous bed or a series of lenses grading upward and laterally into the breccia.

I have not had the opportunity to observe directly the movement of an active block lava flow. However, a photograph by Einarsson (1949, plate 3, fig. 1) demonstrates clearly that the dense lava of the 1947-48 eruption of Hekla is typical block lava. Einarsson's excellent description of the movement of this type of flow (1949, pp. 26-30) during the Hekla eruption indicates a close similarity to the movement of aa, except possibly for a greater degree of separation into discrete plastic layers within the flow and more abundant formation of "toothpaste" type tongues.

Examination of old flows suggests that block lava flows more commonly advance by sliding or gliding over the surface of the underlying material than do aa flows. In some instances they act as plows, in much the same manner as some glaciers. Advancing over soft material they may push some of it up ahead of them, and they may locally groove and striate the underlying surface. Probably the sliding motion is restricted to the portion of the flow close to the advancing front, and movement farther back in the flow takes place by true viscous flowage.

REASONS FOR THE DIFFERENCE BETWEEN AA AND PAHOEHOE

The reasons for the formation of pahoehoe and aa have long been a subject of debate. The facts bearing on the problem are as follows:

1. Both pahoehoe and aa commonly form in the same flow.

2. There is no appreciable difference in chemical composition between the solidified pahoehoe and aa of the same flow, although there may be a slightly higher degree of oxidation of the iron in the aa (Washington, 1923).

3. A flow of pahoehoe may change downslope to aa, but the change of aa to pahoehoe has never been observed.

4. Floods of highly gas-charged lava near the vents in early stages of Hawaiian eruptions are always pahoehoe, which commonly changes to aa only a short distance downslope.

5. In contrast, during long eruptions, after the initial lava fountaining dies down, flows of pahoehoe may develop which continue for great distances down the mountainside before changing to aa. Some, such as the 1881 flow of Mauna Loa, may remain pahoehoe to their ends.

6. Pahoehoe commonly changes to aa where it pours over a cliff or steep slope, and the flow remains aa for the remainder of its course below the escarpment.

7. Both pahoehoe and aa, on remelting in the laboratory, yield aa when stirred (Emerson, 1926).

8. Pahoehoe tends to be more vesicular than aa.

9. The vesicle shapes of pahoehoe typically are regular spheroids and clusters of spheroids; those of aa are exceedingly irregular and much deformed.

10. An active pahoehoe flow appears to give off more gas than aa. Thus during the 1950 eruption of Mauna Loa it was impossible to approach close to the lee side of the pahoehoe river near the vents, because of the large amounts of choking gas being liberated. In contrast, although the intense radiant heat and the oxygen-deficient hot air made it decidedly uncomfortable, it was possible to cross the slow-moving marginal fields of the aa flows farther downslope and approach the edge of the main river without detecting more than slight traces of gas.

11. An active pahoehoe flow is in general more mobile and freely flowing, and therefore less viscous, than aa.

12. The groundmass of the central part of a pahoehoe flow is more commonly partly glassy than that of the corresponding part of an aa flow, in flows of the same composition and of comparable thickness.

13. Commonly, although not always, active pahoehoe flows have a tough flexible skin capable of undergoing much stretching and distortion without fracturing.

14. In general, the temperature of liquid pahoehoe appears to be higher than that of aa. During the 1950 eruption of Mauna Loa the temperature of the pahoehoe river near the vents was close to 1050° C., whereas that of the aa river on the lower slopes of the mountain ranged from about 900° to 920°. Crusts

PLATE 3

Fig. 1. Clinkery top of the southernmost aa lava flow of 1950 near the highway on the western slope of Mauna Loa. The jagged crag (or "sprout") in the center is about 5 feet high, and is continuous with the massive central phase of the flow.

Fig. 2. Cross section of the upper part of an aa flow formed in 1920 on the southwest rift of Kilauea, exposed in a crack. The massive central phase of the flow grades upward into a clinkery layer only about 4 inches thick. Most of the fragments of clinker were never detached, but remain firmly anchored to the massive phase. The camera case, about 6 inches long, is lying on top of the flow.

PLATE 4

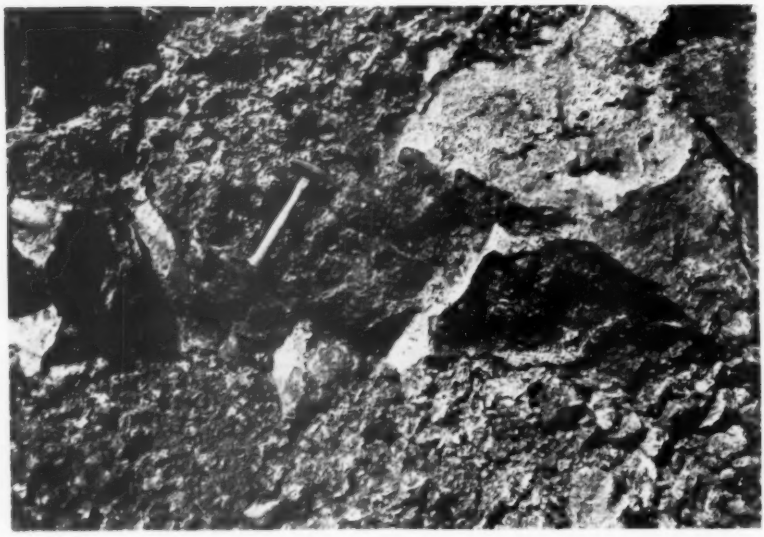

Fig. 1. Massive central phase of an aa flow grading upward and downward into clinkery fragmental material, on Hawaii National Park truck trail on the southeastern slope of Mauna Loa. Note the irregular shapes of the vesicles in the massive phase.

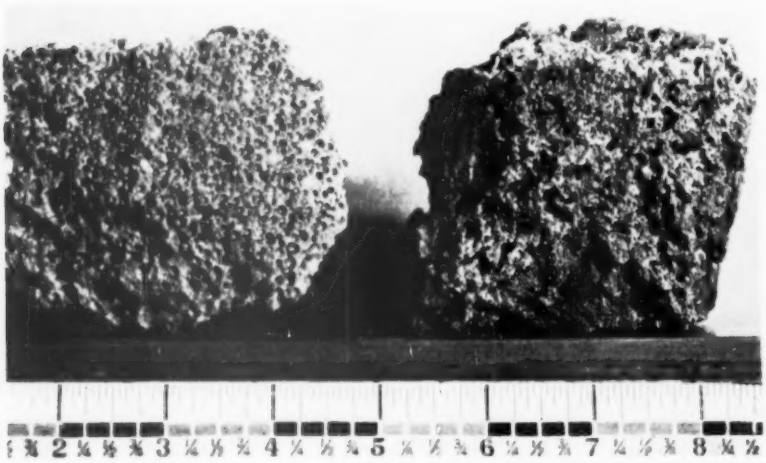

Fig. 2. Hand specimens of pahoehoe (left) and aa (right) showing the marked contrast in typical vesicle shapes. The scale at the bottom is in inches.

PLATE 5

Fig. 1. Advancing front of an aa flow about 50 feet thick, during the 1950 eruption of Mauna Loa. The surface and front of the flow are largely loose clinker. In the center of the front a fragment has just broken loose, revealing hot glowing pasty material. At the left a cloud of dust is rising where fragments are rolling down the front.

Fig. 2. Fragmental phase of a block lava flow near Cinder Cone, Lassen National Park, California. Note the regularity and smoothness of the blocks. The fragments average about 6 inches across. Photo by R. H. Finch.

were forming on both rivers, but more abundantly on the pahoehoe.

Dutton (1884) called attention to the greater viscosity of liquid aa as compared to pahoehoe, and attributed its formation to the fragmentation of the upper part of the flow by movement of the viscous fluid beneath. He says (p. 96): "The fields of aa are formed by the flowing of large masses of lava while in a condition approaching that of solidification. . . . A mass so large but still plastic undergoes, for a considerable time, a slow movement amounting to perhaps a few hundred feet in a single day. . . . During this slow glacier-like motion crushing strains of great intensity are set up throughout the entire mass, and its behavior conforms strictly to that of viscous bodies. The superficial portions in part yield plastically to the strains, in part yield by crushing, splintering, and fissuring. The result is a chaos of angular fragments." So far as it goes, Dutton's deduction is correct, and the process he pictures is an important part of the total process of formation of aa. The fact that the movement of the flow need not be slow (some aa flows during the 1950 eruption of Mauna Loa advanced at a rate of more than 2 miles an hour) is not important. Dutton's picture does not, however, explain and correlate many minor features of the flows, nor explain in more than a very general way the reason for the greater viscosity of aa. Furthermore, it appears probable that absolute viscosity is not an adequate explanation. Although actual measurements of their viscosity are lacking, it appears quite certain that liquid lava of approximately the same viscosity may under different conditions form either pahoehoe or aa.

It appears definitely established that there is no significant difference in chemical composition between aa and pahoehoe, so far as the fixed constituents are concerned. The slightly greater oxidation of the iron in the aa, commonly evidenced in the field by the brownish hue of the clinker, does not appear to be important and results largely from the easier access of air to interior parts of the aa flow. There may, however, have been a difference in the fugitive constituents while the lavas were still mobile. There is no way of measuring the gas content directly, but several of the features listed above indicate with a considerable degree of certainty that mobile pahoehoe is richer in gas than is mobile aa. This is just the opposite of the state-

ment by some volcanologists that pahoehoe is poor and aa rich in gas (Washington, 1923, p. 419; Escher, 1929, p. 136; Rittmann, 1936, p. 56; Perret, 1950, p. 50). Inasmuch as pahoehoe is frequently observed to change downslope to aa, but the reverse change is unknown, it appears obvious that pahoehoe is the more primitive form.

It has been suggested that the essential feature in the formation of pahoehoe may be the presence on the flow of a tough, flexible glassy skin. The importance of the flexible skin in determining the formation of pahoehoe rather than aa is difficult to evaluate. Certainly a flexible skin is a common feature of pahoehoe, and undoubtedly some of the surface forms characteristic of pahoehoe, such as the ropy surfaces, depend for their formation on a flexible crust which can be deformed without fracture by the movement of liquid beneath. On the other hand, aa surfaces also sometimes show ropy structure, obviously resulting from plastic deformation of the crust. The writer has observed typical pahoehoe toes swelling up as they roll forward, the dark crust rifting and pulling apart, revealing the underlying material as a network of glowing orange-red lines. Obviously, in these the outer crust was not sufficiently flexible to stretch without fracturing. It may, however, have been underlain by a flexible layer between the relatively cool fracturing surface and the molten core. Possibly, instead of being essential to the formation of pahoehoe, the flexible crust is merely a typical characteristic of liquid lava in the physical state appropriate to form pahoehoe.

The greater degree of crystallinity in the central massive phase of aa flows, as compared to pahoehoe, is certainly very general. It may be partly the result of stirring, which promotes crystallization. The expansion of the gas in the pahoehoe vesicles results in some cooling, which undoubtedly contributes to the chilling which causes the formation of large amounts of glass in some pahoehoe flows. In some flows a thin layer of glass directly surrounding the vesicles appears with little question to be the result of this expansion cooling. However, the expansion of the gases to form the vesicles in aa must also have caused cooling of the surrounding liquid. Cooling caused by gas expansion probably is not the cause of the systematically greater proportion of glass in the pahoehoe.

One of the essential differences between pahoehoe and aa appears to be that the gases in the pahoehoe were still expanding when the lava stiffened to immobility, whereas in the aa the gases had accomplished most of their expansion while the lava was still flowing. This was clearly recognized by Jaggar (1920, pp. 167-168), who termed pahoehoe "live lava" and aa "dead lava." The vesicles in the pahoehoe are smooth and regular. They may be somewhat stretched by flowage, but the forms are still essentially those determined by the expanding gas bubbles (plate 4, fig. 2). In contrast, the vesicles of the aa are very irregular, and must have been twisted out of shape by the movement of the lava after the gas bubbles had stopped expanding sufficiently actively to maintain a spheroidal shape in spite of distortion by the enclosing liquid.

As shown in the experiments by Emerson (1926), the loss of gas while the lava is still flowing, resulting in the change from pahoehoe to aa, may be at least partly caused by mechanical stirring. This effect is evident at many places in the change of a flow from pahoehoe to aa where it descends an abrupt slope. Thus during the 1942 eruption of Mauna Loa highly gas-charged pahoehoe which cascaded into a small pit crater at 12,700 feet altitude formed heaps of aa at the foot of the cliff. Once changed, the flow remains aa to its terminus. Similarly, violent stirring by the lava fountains during the early part of an eruption may result in sufficient loss of gas to account for the early flows commonly changing to aa near the vent, whereas later flows, retaining more of their gas, may remain pahoehoe for great distances down the mountainside. Likewise, at least some examples of aa issuing directly from the vent may be the result of stirring by gas liberation in the vent before extrusion.

The characteristic spinose top of an aa flow probably also is the result in part of continued agitation of the lava after the gases have ceased active expansion and crystallization has advanced to the point of imparting a definite granularity to the material. A close analogy exists in the making of fudge, wherein if the candy is poured or otherwise agitated after crystallization has advanced beyond a certain stage there results a rough, spinose, somewhat granular surface akin to the surface of aa. The commonly fragmental character of the aa surface results

from the mechanical fragmentation of the upper part of the flow caused by stresses induced by the moving fluid beneath. Various workers in Hawaii, as well as elsewhere (Krauskopf, 1948, p. 1275), have observed the breaking up of the moving flow surface. Undoubtedly the rough, spinose surfaces of individual fragments of clinker result in part from the pulling apart of blocks of still plastic flow crust. Wood (1917, p. 334) states: "The rough, pointed, and edged texture of the natural aa surface was *seen* [the italics are Wood's] in some cases to be due to the drawing out of points and the shaping of rough edges as the blocks were tilted and rotated away from each other and from the plastic matrix within, while the forward bulging motion was taking place." That this cannot be the sole cause is evident, however, when it is remembered that the characteristic spinose and granular surface is present also in those places on aa flows where the fragmental layer is absent, and the formation of the spinose surface has been observed where no pulling apart of crustal fragments was involved.

CONCLUSION

It is concluded that the formation of aa instead of pahoehoe is at least largely the result of greater viscosity resulting from cooling, loss of dissolved gas, and greater degree of crystallization. The last two factors are promoted by turbulence and internal shearing, and may result from violent stirring by fountain action at the vents or by turbulence in pouring over a steep slope, or merely from prolonged flowage to great distance from the vent. If the lava is erupted quietly and the flow descends no escarpments, the crusting over and the formation of tubes may so retard the loss of heat and gases that the lava will remain pahoehoe to great distances from the vent. The greater amount of glass in pahoehoe undoubtedly contributes to the toughness and flexibility of the confining skin which is evident in the formation of the typical pahoehoe toes. When active flowage continues after loss of gas and cooling have brought about sufficient crystallization to impart a definite granularity to the magma, the typical spinosity of aa results, both on unfragmented surfaces and on the surfaces of the clinker fragments.

The factor determining whether pahoehoe or aa is formed appears to be a critical relationship involving both viscosity and the amount of internal disturbance owing to flowage. With

rapid flow on a steep slope the fragmentation may take place in lava of such a viscosity that it would remain pahoehoe on a gentler slope. When the critical relationship between viscosity and flowage is reached the continuous confining surface of the flow is broken up and the upper part of the flow is fractured into fragments. The spinose character of the surface of the fragments results partly from the pulling apart of still plastic surfaces and partly from the same granularity which produces the spinose character on the unbroken aa surfaces. The fragments continue to be modified in shape by slight plastic deformation and by attrition against each other in the moving flow top.

The subject of viscosity relationships within the flow, and the relationship of viscosity to the degree of turbulence causing fragmentation must at present be left rather vague and wholly qualitative. As yet we have very little quantitative information on the viscosity of lava flows, even in general (Wentworth, Carson, and Finch, 1945, p. 103), and none at all on the variations of viscosity within flows, either aa or pahoehoe. Furthermore the mathematical treatment is greatly complicated, or rendered impossible, by the nonhomogeneity of the liquid involved. Especially in the more advanced stages of consolidation the large proportion of solid crystalline material in the magma may make totally invalid its theoretical treatment as a true liquid.

Pahoehoe is much less common at central volcanoes on the continents, even those erupting basaltic lavas, than it is at the Hawaiian volcanoes. This, no doubt, is related to greater viscosity of the lavas at continental volcanoes, and the greater viscosity may in turn be related to more explosive eruption with a greater degree of stirring out of the dissolved gas at the vent. Because the explosiveness of the eruption probably also increases with increase of viscosity of the lava reaching the surface, the effect is self-multiplying, a small increase in the viscosity of the lava rising from depth producing a great decrease in the proportion of pahoehoe formed. However, as recently pointed out by Verhoogen (1951), viscosity is only one of several factors determining the explosivity of a volcanic eruption. It is probable that an increase in explosivity, for whatever cause, would tend to decrease the proportion of pahoehoe formed.

The granulation point and the fragmentation point are generally close together in basaltic rocks, so that fragmentation of the flow top and development of the exceedingly rough spinose character commonly take place essentially simultaneously, although granulation may occur a little in advance of fragmentation and give rise to the unbroken spinose aa surfaces. In more salic lavas the greater viscosity results in fragmentation at a lower degree of crystallization. The fragments are glassier, do not develop the spinose character resulting from granularity, and because of the lesser plasticity do not develop any appreciable spinose character by pulling apart of the blocks. The more salic the lava, the less spinose and more regular in outline the individual blocks become, until the typical block lava is reached. The mode of formation of block lava thus is one of mechanical fragmentation during flowage similar to that which produces the fragmental tops of aa flows. Owing to the greater viscosity, the fragmentation is commonly more extreme, and produces a greater proportion of fragmental material. The critical relationship of viscosity and flowage thus produces a series of forms which, as pointed out by Jones (1943), is continuous from pahoehoe through aa to block lava.

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A FURTHER TEST OF DIMENSIONAL ORIENTATION OF QUARTZ GRAINS IN BRADFORD SAND

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ABSTRACT. The mean inclination of long axes of quartz grains measured in thin section is shown to vary with direction of section; the inclination is most clearly defined, i.e., shows the least spread around the mean, in sections cut parallel to maximum permeability direction. Perfection of orientation is greatest, therefore, parallel to maximum permeability direction. On the other hand direction of section does not appear to have any significant effect on axial ratio of grains, i.e., the measured shape (approximately sphericity) is not affected by the direction of section in this core.

The statistical testing of orientation is also briefly discussed and the efficiency of analysis of variance and experimental design emphasized.

ORIENTATION of grains in rocks is a relatively neglected field, and most of the investigations have been concerned either with lattice (or optic) orientation or with dimensional orientation of pebbles. The orientation of quartz grains in sediments is difficult to determine and unless there appears to be an application of some importance such investigations are likely to be long delayed. Recently it has been shown that permeability varies with direction in a rock. Of course, it has long been known that permeability is a directional property and it has been demonstrated empirically that permeability along the bedding usually exceeds that across bedding; now, however, it has been empirically established that permeability varies in different directions within the plane of the bedding (Johnson and Hughes, 1948). Permeability is a property of an aggregate and as it is quite clearly directional it must presumably be associated with some directional property of the aggregate; in the case of sedimentary rocks, composition, size and shape are scalar properties, and orientation of the grains and packing are vector or directional properties. The direction of maximum permeability while definitely some function of fabric may be most closely associated with orientation of grains in sediments.

On this premise and with the encouragement of the Pennsylvania Grade Crude Oil Laboratories at Bradford, Pennsylvania, who supplied the permeability data, we have been in-

vestigating grain or dimensional orientation in sediments for some three years. In our early experiments (Griffiths, 1949) we found that it was difficult to obtain a reliable mean value for dimensional orientation; subsequently we used an experimental design which enabled us to extract operator variation and confirm differences in dimensional orientation (Griffiths and Rosenfeld, 1950). Nevertheless, although differences clearly existed they could only be extracted by prolonged and exceedingly detailed analysis. This was undoubtedly partly to be attributed to our selection of a core of Bradford Sand (P 4-1, op. cit., 1950) which we believed showed a very low degree of perfection of orientation. In order, therefore, to be sure of detecting very small differences, we designed the experiment to isolate variation between thin sections and between operators, which we established as main effects, and we isolated variation between fields as a subsidiary effect. This design led to the measurement of each field in each section by each operator, i.e., total replication. Each operator measured 1000 grains, an impracticable number for routine investigation.

On the basis of this experiment we now decided to choose a more typical core of Bradford Sand and to reduce the number of measurements; we were still interested in the main effects, and from the earlier experiments we learned that operator difference is an important source of variation but that fields within thin sections did not appear to be of immediate importance in the present investigation. In this experiment therefore we combined operator and field sources of variation, i.e., the variation from these two sources was confounded (Snedecor, 1946, p. 79). By this means we reduced the total number of grains to 1000, i.e., 200 per operator, a level well within routine accomplishment. The following account details the results of this experiment.

Description of sample and procedure.—The core chosen for the experiment was a typical sample of Bradford Third Sand (Penn. State Cat. No. 5820, Well No. Exp. 4, 1539.00-1539.35 ft., PL4-IE).[1] The permeability plot is illustrated in figure 1 along with the orientation of the five thin sections cut from the core for our microscopic investigation. The thin sections

[1] Pennsylvania Grade Crude Oil Laboratories, Bradford, Pennsylvania, supplied us with the sample together with the data on directional permeability.

were all cut perpendicular to the bedding; no. 1 was also parallel to the direction of maximum permeability, and thin sections nos. 2, 3, 4, and 5 were cut at intervals successively increasing by 22½° to no. 1; no. 5 was therefore perpendicular to both bedding and maximum permeability direction.

Ten fields were chosen on a random 3, 4, 3 grid across each slide and each of the five operators was assigned, again at random, to two fields per section. Twenty-five grains per field

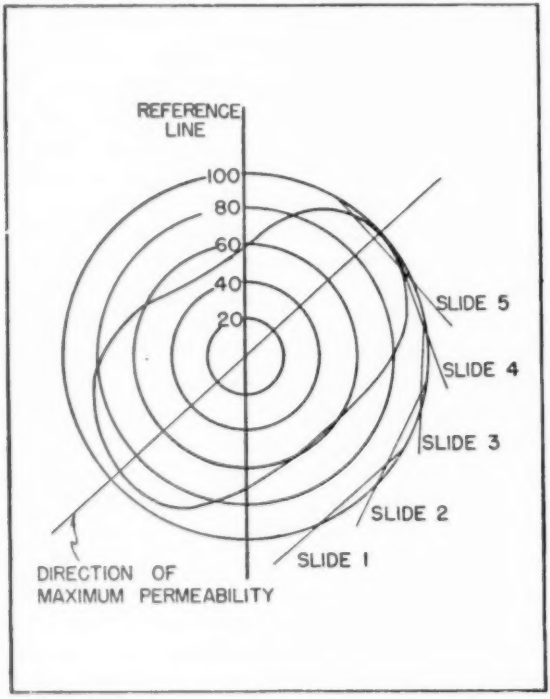

Fig. 1. Permeability plot and thin section orientation for core 5820.

were selected by means of a squared paper grid and their projected images drawn. Thus each operator drew 25 grains from each of two fields per thin section giving a total of 250 grains per thin section.

Using the drawn images, each operator measured the long (a) and short (b) axis of each of his own grains; the results are based upon the manipulation of these data. Details of the

procedure have been described in our earlier publication (Griffiths and Rosenfeld, 1950). As in that earlier investigation the five most circular grains were rejected before measuring the inclination of the long axis to a zero reference plane—referred for convenience to bedding direction. The same reservations apply to the term bedding in this case as in our previous example (ibid, 1950). Our data comprise, therefore, axial ratio (b/a)—a measure of sphericity—on 1250 grains, 250 per thin section, and inclination of long (a) axis—a measure of orientation—on 1000 grains, 200 per thin section.

Statistical treatment of the data.—It is becoming increasingly obvious that statistical treatment of problems in the broad field of geology is of tremendous advantage; it is, of course, full time for geologists to adopt a more rigorous approach and for subjective description and "authoritative" opinion to yield to objective measurement and enumeration of data. What is not so often stressed is the value of the statistical approach in designing the experiment. The following account is an example of the premises of the argument leading to an experimental design for the present investigation.

The first step is to formulate a question; for example, in the present investigation our two main questions are:

1. Does the mean inclination of quartz grains differ in different directions in the core 5820 of Bradford Sand?

2. Does the axial ratio of quartz grains vary in different directions in core 5820 of Bradford Sand?

The next step is to set up a null hypothesis (Fisher, 1949, p. 15); in our example we formulate one for each question by stating as *a priori* assumption that in fact the inclinations of quartz grains in different directions in core 5820 do not differ and similarly neither does the axial ratio. On this premise every set of measurements we obtain is a sample from the same parent population. Now in practice samples will vary even when drawn from the same parent population and this variation due to random sampling[2] is tabulated in texts on statistics. Our initial basis for judgment, then, is to estimate the magnitude of this variation and compare it with the variation we would expect if our initial hypothesis were correct.

[2] It is customary to specify the population as normal but considerable departures from the ideal form are permissible in practice.

This is the simplest case, but even if the samples are indeed drawn from a homogeneous parent population there are other sources which would give rise to variation in the results and strictly there are an infinite number of such sources. It is necessary therefore to extract in some way the magnitude of the variation to be attributed to as many of these sources as possible in order to ensure that they do not interfere with the comparisons we wish to make. Our main interest concerns the variation—in both inclination of long axis and axial ratio of quartz grains—which arises from differences between thin sections. We know from our earlier tests that differences between operators contribute to variation and this we wish to remove. Also on the basis of our earlier work we know that there are two possibilities involved in this operator variation: firstly, some operators tend to measure high values and others low values: secondly, some operators are consistent, e.g., measure high all the time, whereas others are inconsistent, sometimes measuring high values and at others low values. Both these sources of variation are included in our experimental design. The two sources, differences between direction of section and differences between operators, are our main effects, and the inconsistency of operator from thin section to thin section determines the sensitivity of the tests for these two effects. The inconsistency is measured by the interaction term (Youden, 1951, p. 59 ff.). If the variation contributed by this inconsistency is high, then differences attributable to main effects must be large to be detectable. The inconsistency or interaction term is the "error" term for these comparisons. After segregating the variation associated with these three sources we are still left with variation which we have not specified, and this is generally considered to be variation from unassigned sources. The magnitude of this contribution becomes our measure of "error" for the experiment as a whole.

Variation will be estimated as variance (standard deviation squared) and the experimental design leads to a statistical treatment of the data known as the analysis of variance.[3] The whole experiment may now be summarized in the form of a

[3] Analysis of variance is described in most statistical texts (e.g., Fisher, 1946, Snedecor, 1946, Youden, 1951, etc.), and examples of the use of this statistical technique in similar problems are given in Griffiths and Rosenfeld, 1950, and Rosenfeld and Griffiths, 1950.

mathematical model which indicates the steps to be taken in this analysis of variance (table 1).

TABLE 1

SOURCE OF VARIATION	DEGREES OF FREEDOM	SUM OF SQUARES	MEAN SQUARE	COMPONENTS OF VARIANCE
THIN SECTIONS TS	$(n-1)$	$\sum_{1}^{n}\left(\sum_{1}^{kg} x\right)^2 / _{kg} - CT$	$\frac{SS_{TS}}{(n-1)}$	$s^2 + gs^2_{OTS} + ngs^2_{TS}$
OPERATORS O	$(k-1)$	$\sum_{1}^{k}\left(\sum_{1}^{ng} x\right)^2 / _{ng} - CT$	$\frac{SS_O}{(k-1)}$	$s^2 + gs^2_{OTS} + kgs^2_O$
OPERATORS x THIN SECTIONS O·TS	$(n-1)(k-1)$	$\sum_{1}^{kn}\left(\sum_{1}^{g} x\right)^2 / _{g} - CT - SS_{TS} - SS_O$	$\frac{SS_{OTS}}{(n-1)(k-1)}$	$s^2 + gs^2_{OTS}$
UNASSIGNED SOURCES (ERROR)	$nk(g-1)$	$\sum_{1}^{nkg} x^2 - CT - SS_{TS} - SS_O - SS_{OTS}$	$\frac{SS_E}{nk(g-1)}$	s^2
TOTAL	$(nkg-1)$	$\sum_{1}^{nkg} x^2 - CT$		

Where: $CT = \left(\sum_{1}^{nkg} x\right)^2 / _{nkg}$ *and:* n = no. of thin sections; k = no. of operators; g = no. of grains

DESCRIPTION OF THE RESULTS

The axial ratio means for each operator over each slide based on 25 grains from each of two fields per thin section are listed in table 2. The right hand marginal column contains the thin section means over all operators and the last row of the table contains the means for each operator over all thin sections. In the last cell of the table the overall grand mean is recorded. The analysis of variance of axial ratio measurements in table 3 is based on a comparison of these means, and the procedure is best explained by describing the steps involved in obtaining inferences about the differences between these means from a comparison of variance using the F or variance ratio test.

TABLE 2

Axial Ratio Means for each Operator and each Thin Section of Core 5820

Operator	A	B	C	D	E	Thin Section Means
Thin Section·						
1	0.68146	0.68656	0.64324	0.64054	0.62976	0.656312
2	0.65348	0.59304	0.61602	0.69040	0.59836	0.63026
3	0.66704	0.66436	0.66936	0.62754	0.65210	0.65608
4	0.69232	0.67128	0.60618	0.66530	0.63412	0.65384
5	0.66964	0.64590	0.67150	0.65002	0.64360	0.656132
Operator Means	0.672788	0.652228	0.64126	0.65476	0.631588	0.6505248

TABLE 3

Analysis of Variance for Axial Ratio Measurements of Bradford Sand Core 5820

(1)	(2)	(3)	(4)	(5)	(6)	(7)
Source of Variation	D.F.	Sum of Squares	Mean Square	F	$F_{.05}$	$F_{.01}$
Thin Sections	4	0.12937	0.03234	1.435	2.38	3.34
Operators	4	0.24024	0.06006	2.665*	2.38	3.34
Operators x Thin Sections	16	0.55593	0.03474	1.55	1.65	2.01
Unassigned Sources or Error Term	1225	27.40420	0.02237	...	...	..
Total	1249	28.32974	.....	...	...	...

Pooled error mean square 0.022530 with 1241 degrees of freedom

Firstly the mathematical model (table 1) suffices to explain the meaning and derivation of columns 1 and 2. The figures in columns 3 and 4 are obtained from the raw data in terms of sums of squares as shown in the model. Column 5 lists the results of variance ratio testing, and columns 6 and 7 contain F values, taken from the tabulated F distribution (Snedecor, 1946, pp. 222-225), that must be exceeded to indicate significance at the 5 and 1 per cent levels.

To understand the steps involved in obtaining the F values in column 5 it is necessary to return to the components of variance listed in the model, table 1. There the contribution to variance from unassigned sources, i.e., the experimental error for the whole experiment, is designated s^2 and equals 0.02237 in table 3. The interaction term operators times thin sections comprises contributions from error (s^2) and from the inconsistency of operators from section to section (gs^2 o.ts); we test the significance of the interaction term against the error term yielding the variance ratio $(s^2 + gs^2 \text{ o.ts})/s^2$ which will approach unity as gs^2 o.ts approaches zero. In effect we are assuming that the contribution to variance from the inconsistency of operators over thin sections does not exceed the contribution from the error term. The variance ratio yields an F value of 1.55. The tabulated values of the F distribution list

a value of 1.64 at the 5 per cent level. We expect to find this variance ratio exceeded in some 5 cases out of every one hundred on average even in random sampling from a homogeneous population; our observed value of 1.55 is therefore likely to occur more frequently (in fact more often than 10 times but less than 20 or $P > 10 < 20$, Fisher and Yates, 1948, pp. 35-37). On the basis of this test then, the interaction term is an independent estimate of error and we may pool the two terms to obtain a more efficient estimate. To obtain a pooled value it is necessary to return to the sums of squares of table 3 and add them and divide by the summed degrees of freedom. Our new estimate is 0.022530 with 1241 degrees of freedom.

In testing the main effects, differences between thin sections and differences between operators, the components of variance indicate that the logical error term is the interaction, but since in this case the interaction and error term are estimates of the same population value, the pooled error becomes our basis of testing. Again we set up our hypothesis that the means from each thin section are representative of samples from the same populations and through the variance ratio estimate whether such results are likely. In the case of the axial ratios no significant differences are found and we accept the hypothesis, i.e., the set of measurements from each thin section represent in fact five samples from the same population.

The operators tested in a similar manner yield a variance ratio which exceeds that at the 5 per cent level of the F distribution (see table 3), i.e., such a difference would arise if the results of each of the operators were in fact samples from the same population about 5 times in 100. It is clear, therefore, that operator differences are larger than thin section differences and that it is necessary to remove this effect to obtain an efficient estimate of differences between thin sections. It should be clear too that by randomising operators over thin sections the differences are effectively removed as shown by the non-significant interaction.

Our conclusion is, therefore, that the axial ratios of quartz grains as measured in thin sections cut in different directions are not materially affected by the direction in which the section is cut in core 5820 of Bradford Sand.

The means for the inclination of the long axes of quartz grains are listed in table 4 (based on 200 grains per operator

per thin section), and the analysis of variance is summarized in table 5.

TABLE 4

Mean Inclination in Degrees of the Long Axis of Quartz Grains in Thin Sections of Core 5820 Bradford Sand

Operator / Thin Section	A	B	C	D	E	Thin Section Means
1	−1.8875	+1.375	+2.425	+2.400	−0.200	+0.822
2	+10.4125	+10.70	+9.2375	+4.912	+13.40	+9.732
3	+18.4375	+12.15	+8.35	+18.75	+9.725	+13.482
4	+19.90	+7.13	−1.9125	+9.562	+18.8375	+10.705
5	+6.1375	−8.100	+6.55	+25.25	+2.225	+6.412
Operator Means	+10.60	+4.65	+4.93	+12.175	+8.80	$\bar{x}_G$ +8.231

$\bar{x}_G$ = grand mean.

TABLE 5

Analysis of Variance of the Inclination of Long Axis from Core 5820, Bradford Sand

Source of Variation	D. F.	Sum of Squares	Mean Square	F	$F_{.05}$	$F_{.01}$	$F_{.001}$
Thin Sections	4	18,829.25	4707.31	3.55**	2.38	3.34	4.62
Operators	4	9,038.10	2259.53	1.706	2.38	—	—
Operators x Thin Sections	16	33,106.95	2069.18	1.577	1.65	—	—
Error	975	1,279,099.34	1311.90	....	...	...	...
Total	999	1,340,073.64	—	....	...	...	...

** Pooled error = 1324.12, D. F. 991

The process of testing is identical with that for the axial ratio measurements, and once more the interaction is not significantly greater than error and these two estimates are therefore pooled. The error is used to test the main effects of thin sections and operators. Now, however, we find differences between operators are not significant whereas differences between thin sections are significant at the 1 per cent level. In the case of the inclination measurements, then, the observed differences between mean inclination in the thin sections would arise less

than one time in 100 trials by random sampling. Our initial hypothesis is rejected; there are valid differences between the samples represented by the thin sections.

THE IMPLICATION OF THE INTERACTION TERMS

The fact that we have established a difference between the mean inclination of long axis of quartz grains in the five thin

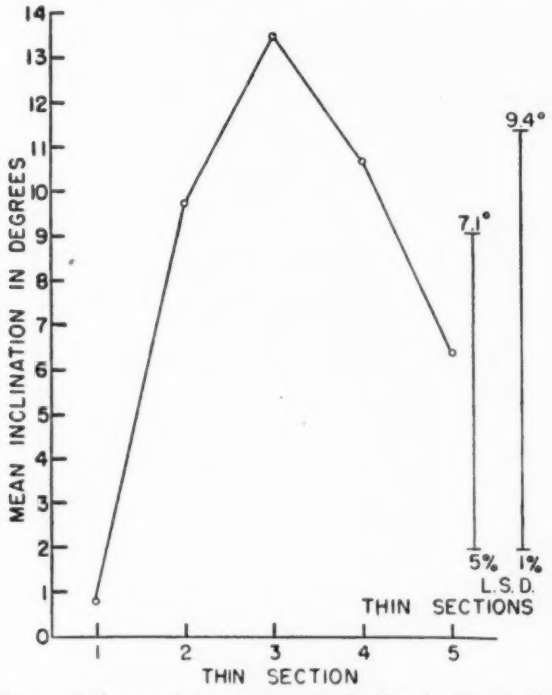

Fig. 2. Difference between mean inclination in thin sections.

sections of core 5820 does not in itself tell us which sections are different. The analysis of variance cannot of itself resolve this problem any farther, and we must use another approach to decide the specific source of the significant differences. We may first examine the differences between the mean values of the axial inclination; thse are illustrated in figure 2. The least significant difference (L.S.D. in fig. 2)[4] suggests that the

[4] See Johnson, L. P. V., 1950, p. 123, for explanation of least significant differences.

mean inclination of slides 1 (parallel to maximum permeability) and 5 (perpendicular to maximum permeability) are significantly different from the mean inclinations of the other slides. This conclusion, interesting as it may be, does not however establish that maximum preferred orientation is parallel to maximum permeability direction.

Let us now examine the interaction term of operators over thin sections. It will be advantageous here to return to the axial ratio measurements first; the means of each operator on each slide are graphed in figure 3. As we know from the analysis of variance that there are no significant differences in this com-

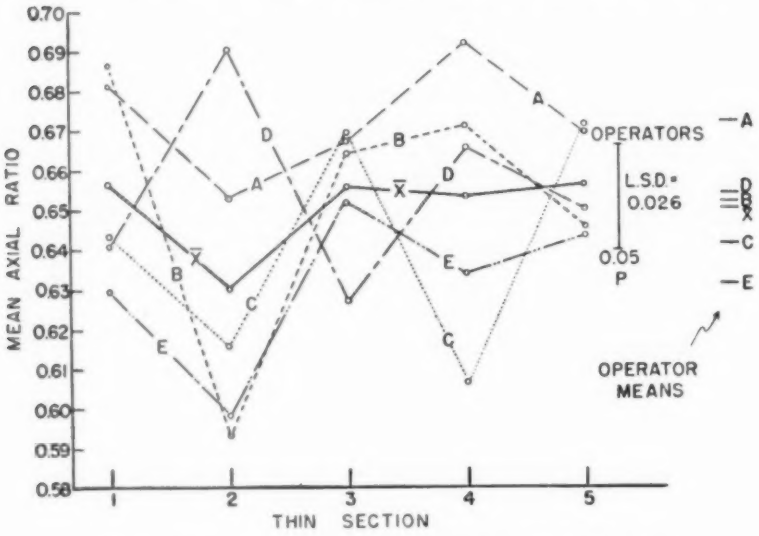

Fig. 3. Interaction thin sections x operators for axial ratios.

parison, it is of general interest to note that operator A remains consistently above the mean value whereas operator E remains consistently below the mean value and the curves for A and E are sensibly parallel. Operators, B, C, D, however cross the mean line, each other, and the curves for A and E. Operators A and E are reasonably consistent whereas B, C, D are inconsistent. The fact that the interaction term is not significant suggests that even the inconsistent operators are not contributing a larger amount of variation to the measurements than the unassigned variation. Nevertheless differences between operators

are barely significant at the .05 level. We can see that in this case confounding operators with fields has not introduced any large component of error into the interaction, and although operators are different the replication over thin sections even using different fields is sufficient to resolve the differences. The ordinate scale of figure 3 is, of course, very much enlarged.

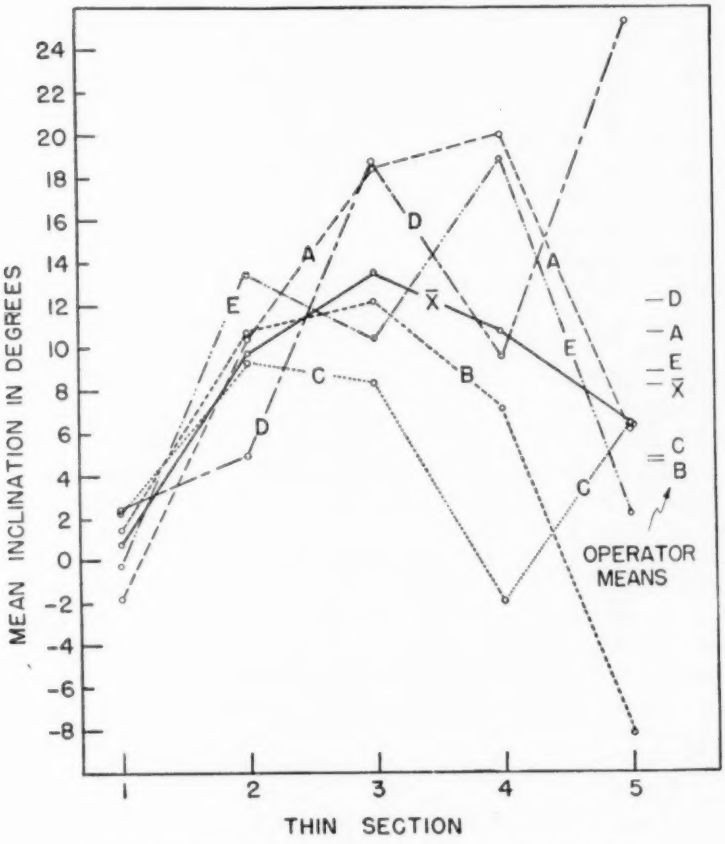

Fig. 4. Interaction thin sections x operators for inclination of long axes.

Turning now to the interaction term of the inclination experiment the means for each operator on each slide are portrayed in figure 4. Again the same two operators A and E are reason-

ably parallel while the other three are not, but the analysis of variance has indicated that whatever differences may be present are not significant and even the differences between operators are not significant. At first sight this about exhausts the possibilities, but it is quite apparent from the graph that the mean inclinations of each operator in thin section 1 are

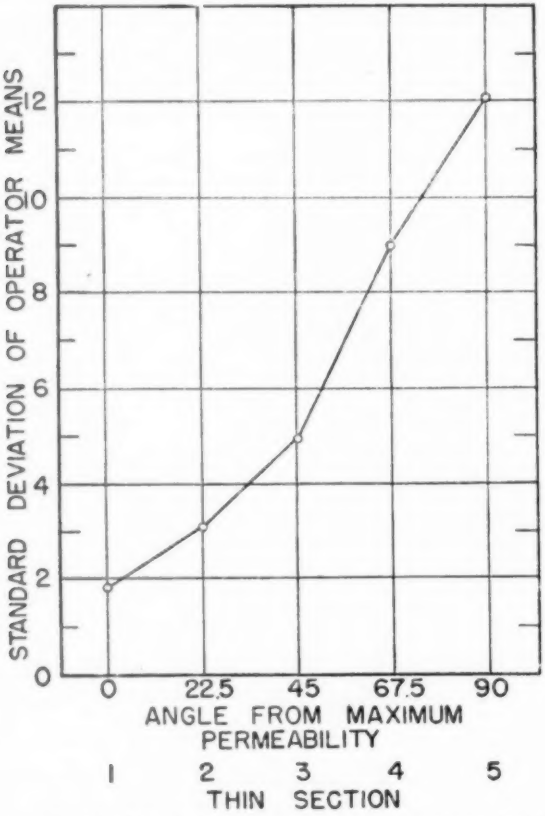

Fig. 5. Standard deviation of operator means versus orientation of thin section.

close together whereas they are very widely spread in thin section 5; indeed this spread gradually increases from section 1 to 5. This feature is best emphasized by plotting the standard deviations of operator means for each thin section; when the sections are arranged in order of increasing departure from

parallelism with the maximum permeability direction, it can be seen (fig. 5) that the standard deviation increases with increasing departure from the maximum permeability direction.

The variances in this case are decidedly heterogeneous as determined by Bartlett's test on the five variances associated with operator means. It must now be recalled that operators and fields are confounded in this experiment, and with this in mind the significant differences between variances may be attributed either to discrepancies between operators over fields or to differences between fields. In the former case if the operators measured grains from the two fields of each thin section consecutively, commencing with thin section 1, then increasing fatigue may have contributed to increasing discrepancy. We have no record of order in this experiment but it appears unlikely that each of five operators used the same order by chance. The alternative—and more attractive—possibility is that grain orientation in different fields of thin section 1 show less variation than in the other four sections. Differences in orientation between fields within thin sections were found in our earlier experiment (Griffiths and Rosenfeld, 1950, table 8). Apparently then the inclination of grains within fields is more consistent in the direction of maximum permeability than in any other direction, which suggests that perfection of parallelism of grains is associated with direction of maximum permeability.

Further consideration of the data.—We may now return to a consideration of the raw data (table 6). The axial ratio measurements show no significant differences between means in the five thin sections and the variances are also homogeneous (Bartlett's test, see Snedecor, 1946, p. 249) so we may combine the measurements for all five sections into a single population (fig. 6). This distribution possesses a mean of 0.6505 and a standard deviation of 0.1505; a chi-square test against normalcy yields $\chi^2 = 15.08$ which for 15 classes yields 12 degrees of freedom and a probability value $P > 20 < 30$, i.e., if the parent population of axial ratios in 5820 is normal, a departure such as that yielded by our sample of 1250 measurements would arise from errors of random sampling more than 20 and less than 30 times in every hundred such sets of 1250 items. The distribution of axial ratios is therefore likely to be normal (fig. 6).

TABLE 6

Summary of Statistical Data on Axial Ratio and Long Axis Inclination in Bradford Sand Core 5820

Slide No.	Axial Ratio				Inclination			Orientation to Maximum Permeability
	$\bar{x}$	s	N	Cv. %	$\bar{x}^\circ$	s°	N.	
1	0.656	0.144	250	21.95	−0.82	37.08	200	Parallel
2	0.630	0.164	250	26.03	9.732	34.60	200	22½°
3	0.656	0.152	250	23.17	13.48	37.22	200	45°
4	0.656	0.142	250	21.65	10.71	34.74	200	67½°
5	0.654	0.152	250	23.25	6.412	37.99	200	90°
All Slides	0.650	0.150	1250	23.08	8.231	36.61	1000	——

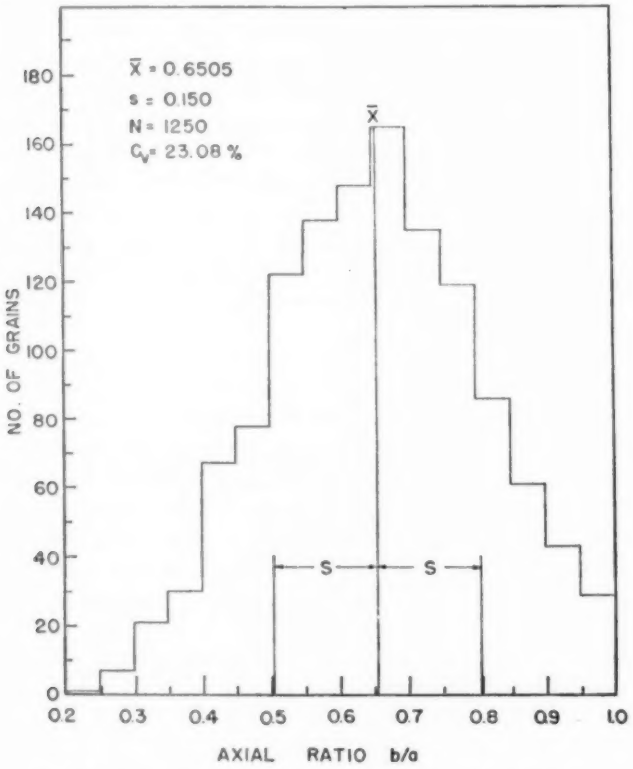

Fig. 6. Normal distribution of combined axial ratios for five thin sections.

Axial ratio is a measure of two dimensional sphericity and it would therefore appear that direction of section has no effect on this measure of sphericity in core 5820. In our earlier experiment there was a significant difference in axial ratio between fields within thin sections and a highly significant difference between thin sections. These findings need more careful evaluation before being elucidated.

In the case of inclination of long axes the distributions differ in mean although on the basis of Bartlett's test the variances are homogeneous. Our interest here centers on the presence or

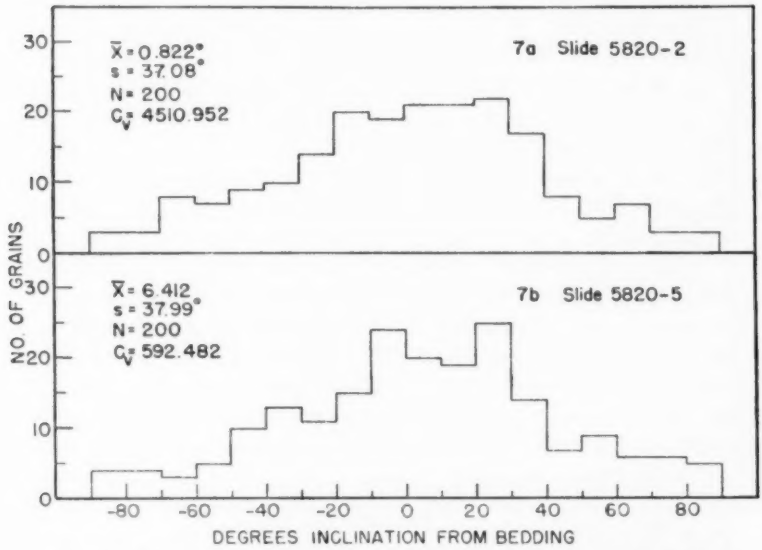

Fig. 7. A. Frequency distribution of inclination of long axis in slide 4.
B. Frequency distribution of inclination of long axis in slide 5.

absence of orientation and two of the slides were chosen for testing. The range of inclination varies from $-90°$ to $+90°$ around $0°$ and if the long axes of the grains were inclined at random then there would be an equal number in each class, i.e., 11.1. We may test the departure of our sample of observations from the theoretically established random distribution by a χ^2 test (Fairbairn, 1949, p. 298). In the case of thin section 1 (fig. 7) we obtained a $\chi^2 = 77.24$ which with 16 classes (or 15 degrees of freedom) yields a probability of <0.01. In other words, if our sample is drawn from a parent population with

inclination of long axes at random, then such a departure from randomness would arise less than one time in 100. We have therefore either to reject the Null Hypothesis (random inclination in parent population) or decide that a very rare event has occurred. We reject the Null Hypothesis and infer the presence of preferred orientation in the parent population of which thin section 1 is a representative.

A similar test on section no. 5 (fig. 7) (perpendicular to bedding and perpendicular to maximum permeability) yields $\chi^2 = 75.94$ which with 15 degrees of freedom yields a probability of 0.01. The implications are identical.

CONCLUSIONS

It seems clear from the results of our experiment that mean inclination differs between slides in different directions within one rock specimen. The perfection of orientation is also a function of direction of section, the section cut parallel to the direction of maximum permeability showing the most perfect parallelism.

Mean inclination measured in these slides is a measure of the imbrication of long axes of quartz grains, and apparently the parallelism of imbrication is most perfect in the direction parallel to maximum permeability. The mean angle of imbrication relies for its meaning on the perfection of parallelism because, although a mean would be obtained from a sample which possessed no preferred orientation, i.e., in which the long axes were inclined at random, such a mean inclination would have little geological significance. If all the grains were aligned in the same direction the parallelism of imbrication would be perfect and mean imbrication would suggest a dominant and consistent single cause. In our case the long axes of grains are oriented and the mean imbrication is most closely specified, i.e., the parallelism as measured by the spread of the inclinations around the mean is an optimum, in a direction parallel to the maximum permeability. The mean imbrication is therefore most meaningful in this direction. The inclination in this core does not differ greatly from horizontal (see table 6, $\bar{x} = -0.82$). In our previous experiments three cores (P4-1, PNY 22-2, PNY 23, Griffiths, 1949; Griffiths and Rosenfeld, 1950) possessed low angle inclination to the horizontal, $-2.72°$, $4.6°$, and $15°$ respectively. Such inclinations measured from a reference direc-

tion which is horizontal in terms of the axes through cylindrical well cores are not very informative. In fact local differences in dip of 15° may be expected and indeed arise from two fairly obvious sources:

1. The mean inclination of long axes of quartz grains may show variations of this magnitude because of local variations of dip.

And/or 2. Small deviations from the vertical during drilling may affect our reference plane so that core horizontality may not coincide with true horizontality.

Similarly single dip values measured on outcrops are unlikely to be of regional significance; moreover in some sediments a micro-bedding may be present inclined to the macro-bedding, the inclination of which to horizontal is usually taken as a measure of dip.

One other factor of importance deserves emphasis; we reduced the number of grains analyzed in the present experiment in an attempt to bring the work within practicable limits for routine analysis, and as a result we confounded operators with field sources of variation. In drawing inferences from the analysis of variance this compelled us to acknowledge an ambiguity; consistency of inclination around means was greatest in the section parallel to maximum permeability, but this may have been due to increasing operator fatigue—which on the basis of our previous experiments we judged to be unlikely—or to the fact that inclination in fields within thin sections is more consistent in this thin section than any other. It is clear that until we know the prime cause of variation in inclination and perfection of the inclination in the long axes of quartz grains in sediments, we lose more than we gain by attempting to reduce the detail of the investigation. This point deserves emphasis mainly because it is a salutory lesson that there are no quick ways to the solution of problems in geology, and until we have learned enough, i.e., collected sufficient data, to be reasonably familiar with the facts we cannot afford to neglect sources of variation which appear to possess only nuisance value to the immediate purpose of an investigation. It should also be clear from a comparison of our first (1949) investigation with the latest experiments that attempts to draw inferences without efficient experimental design are apt to be woefully misleading—and this may be taken as a very general conclusion.

ACKNOWLEDGMENTS

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APPENDIX

DISCUSSION OF THE MEASUREMENT AND TESTING OF ORIENTATION

This experiment was designed to correlate parallelism of orientation of grains with directional permeability; during manipulation of the data a number of statistical techniques were used for testing the observations and because this aspect—testing the observations—is relatively new and has recently been carefully reviewed by Chayes (Fairbairn, 1949, chapters 22, 23) it seems worthwhile to point out some additional difficulties and hazards which have arisen during our experiment.

Firstly our operational definition of orientation is: the inclination of the longest axis of a quartz grain to a fixed reference direction as seen in an oriented thin section. Each grain possesses such an orientation, and it is tacitly assumed that grains tend to orient in parallel by specifying direction of orientation as the mean of a set of such measurements.

It should be clear from the preceding experiment that analysis of variance is our main purpose. This use of the variance (or the square root of the variance, the standard deviation) has been emphasized by Chayes as follows: "Though it may often happen that exact location of the mean is not a matter of great importance, in fabrics of the type we have been discussing the whole difference between a strong orientation and a weak one is just

that the first has a small and the second a large standard deviation" (Fairbairn, 1949, p. 304).

If we admit the restrictions suggested by Chayes, particularly unimodal distribution of the frequencies of inclination, then we can define the problem somewhat more specifically by examining the theoretical range of orientation involved. In the first case if grains all point in the same direction the spread around the mean will be zero and the standard deviation and variance will be zero; such a case is hardly likely in practice even in metamorphic rocks.[5] The other extreme is random distribution (isotropic fabric), and in this case the frequency distribution is, ideally, rectangular.

The standard deviation of a rectangular distribution may be derived as follows:[6]

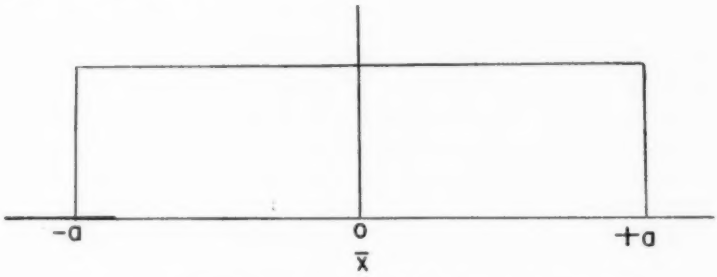

Fig. 8. Rectangular frequency distribution with zero mean.

The equation of a rectangular distribution is $y = f(x)$ in which $f(x) = k$ (constant frequency). The total area under the curve equals 1 and the total area may then be expressed as

$$1 = \int_{-a}^{+a} k\,dx$$

and integrating

$$1 = \Big[k\,x\Big]_{-a}^{+a}$$

$$k = \frac{1}{2a}$$

[5] It should be emphasized that although Fairbairn and Chayes are considering lattice or optic orientation and we are concerned with dimensional orientation the treatment of the data is very closely similar.

[6] Professor Miers demonstrated this derivation to the writers in an informal evening seminar on statistics at The Pennsylvania State College.

The variance for this distribution may now be written

$$\text{variance} = \sigma^2 = \int_{-a}^{+a} \frac{x^2}{2a}\,dx$$

where x^2 is the sum of the squares of the deviations from the mean ($\bar{x} = 0$)

Then $$\int_{-a}^{+a} \frac{x^2}{2a}\,dx = \frac{1}{2a}\left[\frac{x^3}{3}\right]_{-a}^{+a} = \frac{a^2}{3}$$

$$\sigma^2 = \frac{a^2}{3} \quad \text{and} \quad \sigma = \frac{a}{\sqrt{3}}$$

In our experiments the range of the distribution extends from $-90°$ to $+90°$ and hence $a = 90$.

$$\sigma^2 = \frac{(90)^2}{3} = 2700$$

$$\sigma = 51.961°$$

Therefore, the standard deviation for a randomly oriented aggregate is approximately 52° and any oriented aggregate must possess a significantly lesser spread (smaller standard deviation). This last statement is, of course, restricted to frequency distributions which do not depart widely from unimodality.

We may now predict the size of the standard deviation (s_2) which shows a significant departure from randomness and for this purpose we utilize the variance ratio relationship $F = \frac{{s_1}^2}{{s_2}^2}$. In this equality ${s_1}^2$ should always be the larger and we may therefore insert our maximum value for the rectangular distribution (${s_1}^2 = 2700 = {\sigma_1}^2$). ${s_2}^2$ will be our observed variance associated with the measured mean inclination. On the basis of our experiments we may use 200 degrees of freedom[7] for the estimate of F and the values are therefore (Snedecor, 1946, p. 22, and Fisher and Yates, 1948, p. 43):

Degrees of Freedom	$F_{.05}$	$F_{.01}$	$F_{.001}$
Greater Mean Square	200	200	∞
Lesser Mean Square			
200	1.26		
200		1.39	
120			1.56

[7] Strictly 200 grains yield 199 degrees of freedom but such a difference is negligible in the present case.

Returning now to our initial equation we find that, for the variance of our observed distribution to show a significant departure from randomness, the standard deviation must be less than:

Significance level	$P < 0.05$	< 0.01	< 0.001
s_2	46.29	44.07	41.60

Our actual values are all less than 37°, indicating a significant degree of orientation in each case.

Using this measure as a basis of judgment, however, it seems clear from the values in table 6 that the best parallelism or highest degree of orientation is not the direction parallel to the maximum permeability but the direction 22½° oblique to this direction, and if we test the variance ratio of the extreme pair of variances (in directions 22½° and 90° to maximum permeability respectively) we find that the variances of the slides in this table are not significantly different. It seems clear therefore that using total variances for comparison of perfection of parallelism is unlikely to lead to unequivocal decision, and great care must be exercised in estimating the differences in parallelism between slides. Indeed from the results quoted in this report it should be clear that unless the contributions of operators, thin sections and their interaction are segregated it is impossible to demonstrate that perfection of parellelism is actually greatest parallel to the direction of maximum permeability.[8]

The utility of the analysis of variance technique in extracting required information and in segregating variation from sources which serve to confuse the main issues is clear, but it should be emphasized that the entire success of this and our earlier experiments arise from the efficient design of the experiment without which our results would in the very best case have been equivocal.

One other item may perhaps be briefly referred to concerning the testing of orientation; Chayes (Fairbairn, 1949, p. 313) states that "Pending further work on the question, however, it is fair to point out that according to current standards isotropism and preferred orientation are not exclusive alternatives; a disproof of one is not to be construed as a proof of

[8] And strictly the variation from field to field within a single thin section should also be separately evaluated (e.g., Griffiths and Rosenfeld, 1950).

the other," and this statement is somewhat confusing unless considered very carefully. The first impression is that there are other possible alternatives to either randomness or orientation in measuring the directional properties of crystals or grains. This ambiguity is resolved later (ibid., p. 325) but it should be realized in connection with Chayes' statement that the ambiguity is a function of the test, not of the fabric, and the meaning is, of course, "a disproof of one (by a certain statistical test) is not to be construed as (statistical) proof of the other."[9]

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[9] Words in parenthesis inserted by the writers.

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THE GLACIATION OF CENTRAL KEEWATIN, NORTHWEST TERRITORIES, CANADA

J. BRIAN BIRD

ABSTRACT. The country west of Hudson Bay was until recently believed to have been the region from which the hypothetical Keewatin Ice Sheet spread out in the Pleistocene period. In the past few years glaciological, climatological, and other evidence has suggested that a re-examination of the field evidence, on which the theory of a Keewatin center was based, is required. A field and air photograph study, covering an area of 60,000 square miles in central Keewatin shows that the history of the Wisconsin glaciation in the area is complex. Three separate directions of ice flow can be recognized, of which the last two probably originated in the Hudson Bay area. The final ice lobe blocked the natural drainage of the Thelon and Dubawnt rivers, producing an extensive proglacial lake. The level of this lake fell by stages until, when its surface was 360 feet above modern sea level, direct contact was made with the sea.

INTRODUCTION

ALTHOUGH glacial geologists have reached general agreement on the direction of movement and the extent of the Pleistocene ice sheets in southern Canada and northern United States, the Pleistocene history of northern Canada is almost wholly unknown. Among the many problems that are still unsolved is the question of whether the region west of Hudson Bay was at any time the center of a large independent ice sheet. As the result of exploration in Keewatin in 1893 and 1894, J. B. Tyrrell (1897) identified three major centers and one minor center, from which the ice radiated in that region. The first, and probably the earliest, lay between the upper Thelon River and Lake Pelly on the Back River. The second lay between Lakes Dubawnt and Yathkyed; and Tyrrell suggested that in its final stage the ice sheet split into two, a minor center being located north of Baker Lake, while a major center was southeast of Yathkyed Lake. In addition to these centers in Keewatin, Tyrrell also identified a center 100 miles southwest of Churchill. Finally in 1913, he added the Patrician center between Trout Lake and Albany River in northern Ontario. Antevs (1931) accepted the position of Tyrrell's Keewatin and Patrician centers as explaining glacial phenomena in northern Manitoba. Wilson (1939, 1945) also accepted provisionally

the position of these ice centers, after interpreting aerial photographs of eskers in the region north and east of Great Slave Lake.

Further exploration led to the discovery of possibly two additional centers. Burwash (1935) placed one at the east end of Great Slave Lake, and Kidd (1936, p. 16) another on the headwaters of the Back River. The position of these eight centers was deduced from glacial striae. Partly because it is now

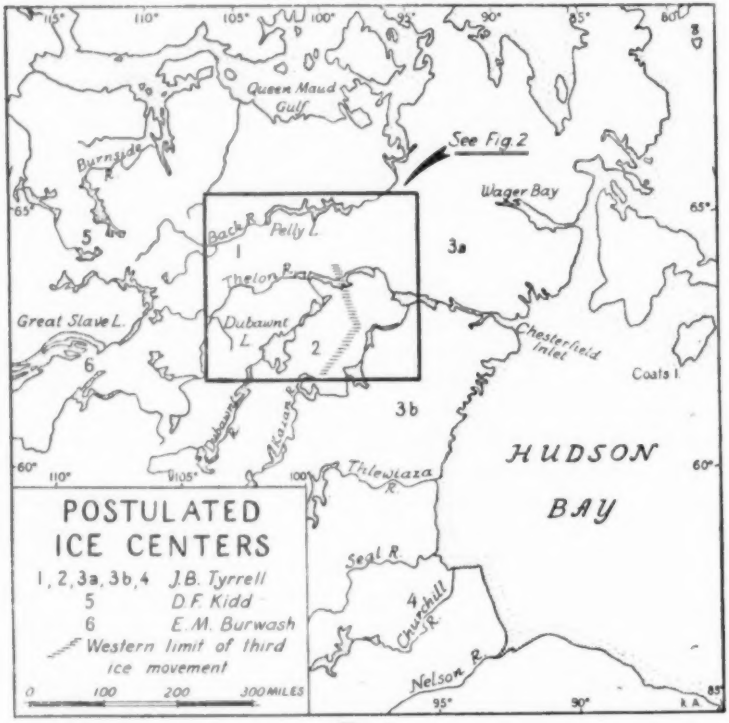


Fig. 1

recognized that striae are an unreliable guide to the direction of regional ice flow, as the lower layers of the ice may be controlled by local topography, and partly because evidence has been produced from other sources, the earlier theories have been challenged.

As early as 1916 Camsell (1916, p. 40) wrote "The evidence (in the Great Slave Lake area) appears to support the idea

of a central gathering ground for a great ice sheet on the east side of Hudson Bay from which the ice moved on the radii of an arc extending from south to west and possibly northwest." Camsell's general hypothesis of a single ice center has been supported by Flint (1943) who stressed the absence of either topographical or climatic controls which would localize ice centers in Keewatin.

There are only three climatological stations in the district from which to deduce the present climate, and only one of these, Chesterfield Inlet, was in continuous operation before 1945. Fortunately the low and uniform relief makes it possible to extend the few precipitation statistics that are available to cover the whole area without great loss in accuracy. Along the Hudson Bay coast the total snowfall in an average year is probably about 5 feet, whilst inland away from the sea it is some 15-20 per cent less. The snow, except in well-protected north-facing hollows, melts very rapidly in the spring often before the mean air temperature has risen above freezing point. Any permanent decrease in temperature would serve rather to lengthen the winter period of low snowfall than to increase the total amount. It seems difficult to conceive of an independent ice cap of large proportions developing in Keewatin, even if summer temperatures were considerably lower, unless the atmospheric circulation was radically changed and the precipitation thereby increased. At the close of an Ice Age, on the other hand, the low annual temperatures might enable small stagnant ice caps to survive long after the main continental ice sheet has disintegrated.

Instead of separate ice centers in Keewatin and Labrador, Flint postulated one east North American ice sheet which first developed in northern Labrador-Quebec, and later reached maximum thickness over the central Hudson Bay region. The weight of this ice sheet depressed the land below sea level, and considerable evidence is found around the shores of Hudson Bay that the land may still not have recovered to its pre-glacial level. The tide gauge records from Churchill which are available from 1928 show that the land may be rising at about 3 feet a century. The presence of submerged valleys on the floor of Hudson Bay that have apparently been eroded by sub-aerial processes (Gutenberg, 1941; Seligman, 1947) is supporting evidence that the floor of the Bay was once above sea level,

and the westward upwarping of the raised beaches on the east side of the Bay (Stanley, 1939) is evidence that when isostatic recovery is complete, the greater part of it may well be so again.

METHOD OF INVESTIGATION

In order to reconcile the conflicting theories based on field work with those from other scientific sources, a more thorough study of the area west of Hudson Bay is required. The short field season, the difficult terrain, and the large area[1] involved prohibit a complete and detailed field study in the forseeable future. It is, however, possible to make field studies in the more accessible key areas and to fill the intervening blank areas from the interpretation of air photographs that are now available for the whole region. One such field study was made in 1948 when a party of four scientists traversed the middle and lower Thelon River by canoe during the summer months. Observations on the glacial geology were made up to a distance of 15 miles on both sides of the main water bodies. This region, to the north of Lakes Dubawnt and Yathkyed, lies within 200 miles of the Keewatin ice centers described by Tyrrell. The study has been extended to the south as far as Dubawnt and Yathkyed lakes, by reference to Tyrrell and air photographs, and north to the Back River from air photographs alone.

The features used by the writer to determine the direction of glacial flow included grooves, striae, eskers, and drumlinoids. As these normally give two possible directions of flow, the true direction was inferred from other evidence, including the position of polished rock surfaces, ice-abraded rock knobs, erratic boulders and the presence of deltaic deposits formed along the ice front in glacial lakes.

GLACIAL STRIAE AND GROOVES

The rock outcrops around the Baker Lake settlement and on the hills to the north of Baker Lake are covered with glacial striae and grooves. The long axis of the striae suggest numerous directions of ice flow. Many of the striae were no doubt formed by boulders embedded in lake and marine ice, when the water level was higher than at present. A series of fifty measurements of

[1] The area of the land west from Hudson Bay to the Mackenzie watershed and from the treeline north to the Arctic Ocean is approximately 250,000 square miles.

striae gave two main directions which were independent of rock exposure. In one group the majority of striae were under 6 inches in length and did not deviate more than 2 degrees from the mean of 286° T. The striae in the second group were mainly over 12 inches in length, and deviated up to 10 degrees from the mean of 333° T. Smoothing and poorly developed quarrying on the sides of rock knobs indicate that the ice moved from the southeast quadrant for both sets of striae. On some surfaces the two sets of striae cross, the 286° group being the earlier.

Between Baker Lake and the west end of Schultz Lake, poorly preserved striae may be found on the majority of rock surfaces. Only one main direction could be determined, the striae varying from 307° to 335°, with a mean of 325°. Many of the local variations are readily explained by the influence of the topography beneath the ice sheet. Roches moutonnées were found on the north side of Schultz Lake, and hills at both ends of the lake show "crag and tail" phenomena. Both indicate that the ice moved from the southeast. The north shore of Schultz Lake forms the boundary between sedimentary rocks to the south and igneous and metamorphic rocks to the north. Scattered erratic sedimentary boulders were found north of this boundary. A prominent green schistose quartzite outcrops in the southeast corner of Schultz Lake. Erratics, apparently from this outcrop, were observed 10 miles to the north. The majority of glacial erratics, however, rarely occur more than 2 miles from the outcrop.

Although isolated striae with bearings similar to the earlier Baker Lake group are found around the lower Thelon and Schultz Lake, it is only between Aberdeen and Schultz lakes that the two well-developed groups appear together. The average direction of the older set in this area is 277°, (270°-284°), and of the newer and better preserved set is 315°. A possible third and less definite set has a mean direction of 330°. Although the bearings of these three groups of striae are relatively close to one another, there is no doubt that the first two were formed by separate movements of the ice since the striae intersect and intermediate bearings are lacking. The third set of striae (at 330°) may indicate the movement of a separate ice lobe, but is more probably associated with the 315° set.

Farther west in the Aberdeen and Beverly lakes region, striae are not as well preserved. The only rock outcrops in the area

are sandstone and conglomerate with infrequent areas of quartzite. Frost action has destroyed much of the glaciated rock surface. The striae are shallow, and are rarely longer than 6 inches. They indicate movement toward 280°, becoming more northerly around Beverly Lake. South of the Thelon along the Dubawnt River, Tyrrell found two sets of striae: an earlier group left by ice moving from the northeast, and a later group made by ice coming from the east and corresponding with the east-west group on the Thelon. The present writer failed to identify with certainty striae of the first group on the Thelon River. Farther east around Yathkyed Lake the main group of striae has an orientation southeast-northwest with the direction of movement somewhat uncertain. The evidence of ice movement from glacial striae therefore suggests three separate motions: the earliest, from the northeast, preserved along the Dubawnt, a second flow from the east and east-southeast preserved in many parts of the Thelon basin, and a third and final movement from the southeast only found in the east of the map area (fig. 2).

DEPOSITIONAL GLACIAL LANDFORMS

Within the area under discussion there are no large unmodified end moraines. Tyrrell believed that the low sandy area between Beverly and Aberdeen lakes was a moraine that had been partly destroyed by lake and marine submergence, following the retreat of the ice. The bedrock of sandstone is here capped with till and fluvial sands, but little evidence can be seen to support a morainic origin either on the surface or in sections made in the superficial deposits exposed in the stream gorges.

Till, in many places of considerable thickness, covers the greater part of the west and center of the area. East of an approximate line from the mouth of the Meadowbank River to Schultz Lake and so to Yathkyed Lake, corresponding roughly with the area underlain by igneous and metamorphic rocks, the till cover is thinner and discontinuous. West of this line the till is generally sandy and variable in thickness. Around Aberdeen Lake the thickness varies from 10 to 50 feet, the till in turn being overlain by water-sorted sands. The greatest thickness of till was found in stream gorges north of Beverly Lake where over 135 feet of homogeneous sandy till almost free from boulders was observed without the base being visible. It was not pos-

sible to determine whether the till deposits are all of one age, but in no locality was more than one deposit found.

The surface of the till is rarely level and featureless. During extended traverses on foot in the Aberdeen Lake area it was recognized that the till surface had a marked pattern, as it was considerably easier to walk in one direction than in the direction at right angles. Close inspection showed that the till had been moulded into low cigar-shaped ridges about ½ mile long and not more than 20 feet high. The long axis of each is parallel to the direction of glaciation as inferred from glacial striae. The ridges are not always recognizable on the ground, but they show up clearly in air photographs, and they do in fact occupy the greater part of the till-covered area. In the southeast part of the map area, where the till is less continuous and has a higher clay content, the ridges assume a low drumlin form. As all stages of modifications are visible from the true drumlin to the long till ridges, it is proposed to use the term "drumlinoid" for this landform.[2] Drumlinoids reach their greatest development, certainly in the area under discussion, and perhaps in the whole of the Canadian Arctic, in the western part of the map area, between the outlet of Dubawnt Lake and the Clarke-Thelon River junction on the south side, and the source of the Consul River on the north side. This region is a vast sandy drumlinoid plain with an area of nearly 10,000 square miles; throughout the plain, except in the few parts where rock ridges stick through the till cover, the shape of the relatively few lakes and the pattern of the stream drainage is totally controlled by the drumlinoids.

Between the Back River lakes and the Thelon River lakes, smaller drumlinoid plains are numerous. They are separated by extremely sandy areas in which the relief is rather greater, generally of the order of about 250 feet, and where small abandoned overflow channels, imperfectly formed eskers, and kettle lakes are numerous. The presence of low parallel end

2 Drumlinoids have been recognized in many parts of the Canadian Arctic (Wilson, 1939, p. 122; Fortier, 1948; Tyrrell, 1897, where they are referred to in some places as Ispatinows—a name that was used earlier by him in the Prairie Provinces—and in others for the first time as drumlinoids) and occasionally in southern Canada (Chapman and Putnam, 1949, p. 31; Tyrrell, 1892, p. 217) where the till is referred to as fluted. Most references (including Washburn, 1947, p. 51) either show or imply that the strike of the drumlinoids is parallel to the direction of glaciation.

moraines along the sides of some of these sandy areas suggests that they may occupy regions of dead ice that survived for a short period after the waning of the main ice sheet.

In the southern half of the map area the orientation of the drumlinoids supports the conclusions of the direction of ice movement that have already been made from the glacial striae, and in addition enables the areas in which the different ice movements were dominant to be mapped with some accuracy. Where two sets of drumlinoids with different orientations are adjacent to each other the terrain between them is often confused and in some cases the two patterns are seen to be superimposed when examined on air photographs. Such is the case along the western limit of the third ice movement (fig. 1) and also between the first and second ice areas northwest of Dubawnt Lake.

North of the Thelon River towards the Back River the drumlinoids show no sudden changes in their orientation, but rather a spreading out of a single ice sheet from a southeasterly direction.

ESKERS

In some parts of central Keewatin eskers are numerous, and are the most prominent feature of the landscape. Although all travelers to the area have noted and commented upon the eskers, it was not until the aerial photography had been completed that it became possible to study their overall pattern. Farther west in the Great Slave Lake area, Wilson (1939, p. 122) has shown that there are two main types of eskers. The two different forms can also be recognized in central Keewatin. The "embankment" type is formed of a single ridge that may run in an unbroken but sinuous line for many miles, the second or "multiple" type consists of a number of closely parallel ridges generally lower and less continuous than the "embankment" eskers, and almost invariably occupying a water-eroded channel in the till.[3] Although exceptions are numerous, particularly north of the Back River, both types of esker are generally restricted to the regions where there is a considerable amount of till. "Embankment" eskers are more common in the drumlinoid areas; "multiple" eskers are typical of the "dead ice" regions.

[3] Wilson used the term "embankment" esker for the first type and "outwash" esker for what is in this paper referred to as a "multiple" esker.

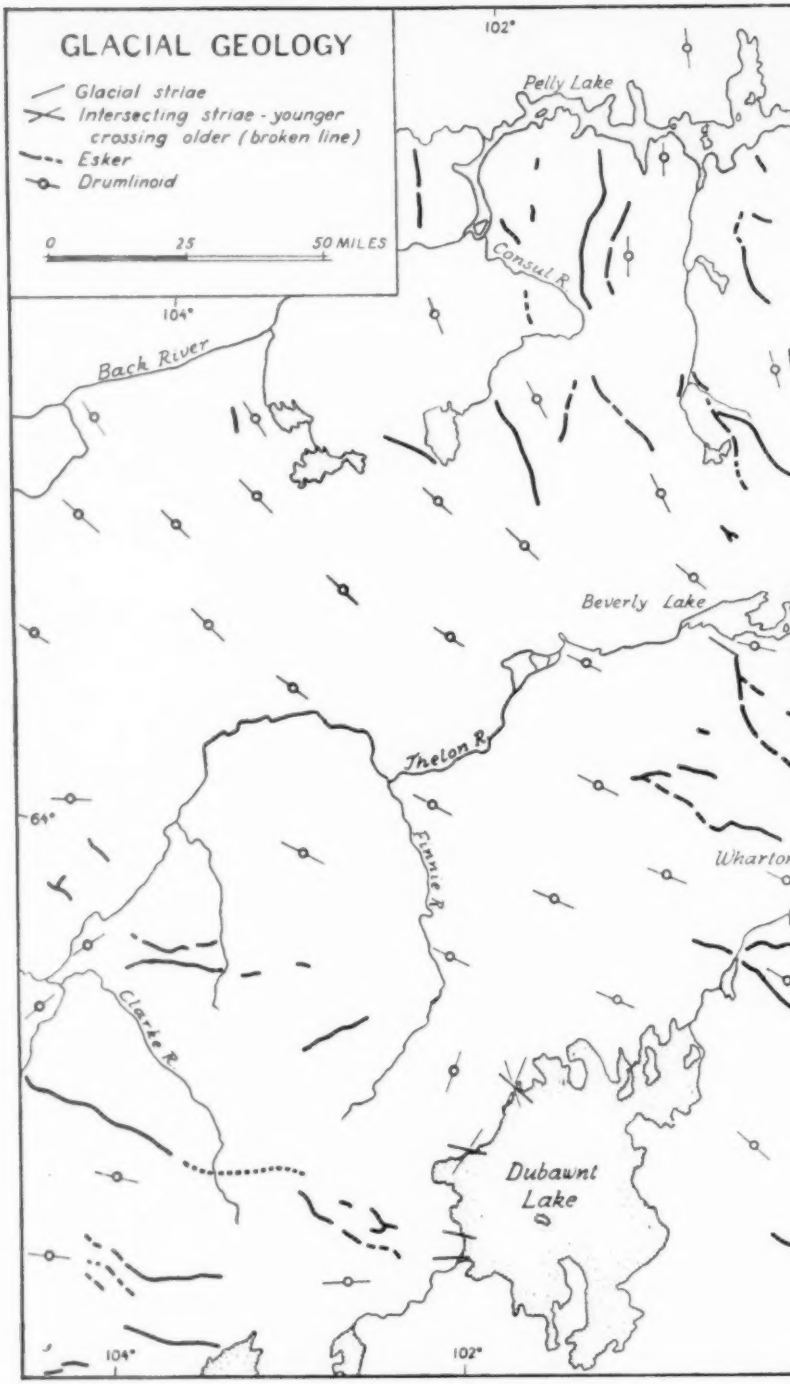
Three main areas of eskers may be recognized from the map (fig. 2). The largest group is in the basin of the Back River. The eskers commence on the north side of the watershed with the Thelon River. It appears from the dendritic pattern of the eskers that they were formed in ice that flowed from the southeast or that at least the surface of the ice was higher in that direction. It is, however, noteworthy that the general slope of the land is also in this direction a regional slope that continues right across the Back River to the Arctic Ocean—and that when the slope is reversed as on the south side of the Thelon watershed, eskers are either very small or nonexistent.

The second group of eskers is found around the lower Dubawnt. They are all of the "embankment" type, and their form suggests that the ice flowed from the easterly quadrant. Related to this group is a line of hills on the southeast side of Beverly Lake which is the most conspicuous glacial landform in central Keewatin. The three main hills forming the group lie on a straight line 9 miles long which parallels the regional flow of the ice in the vicinity. The summit of the highest hill is 500 feet above Beverly Lake and 640 feet above sea level. No rock outcrops were found in the area, and the hills appear to be built entirely of fluvio-glacial material, mainly sand and gravel. Their position close to the confluence of two eskers suggests that they represent the successive deltas laid down at the retreating ice front by the englacial rivers which left the two eskers which extend southeastward from the hills. The esker north of Aberdeen Lake and also the esker north of Mallery Lake have low "delta" sand hills at their western ends.

The third group of eskers in the southwest corner of the map are neither numerous nor very high; their pattern is, however, complicated, particularly around the confluence of the Clarke and Thelon rivers. Perhaps the most surprising feature of the whole map is the absence of eskers from the drumlinoid plain on the north side of the upper Thelon. Elsewhere in Keewatin drumlinoid till plains of this type have been some of the most favorable areas for the development of eskers.

GLACIAL LAKES AND THE POST-GLACIAL SUBMERGENCE

At the period of maximum extension of the ice sheet, a large part of Canada was depressed to a lower altitude than at present. When the ice melted, the land rose, but there was a time


GLACIAL GEOLOGY
Glacial striae
Intersecting striae - younger crossing older (broken line)
Esker
Drumlinoid
0
25
50 MILES
102°
Pelly Lake
Consul R.
104°
Back River
Beverly Lake
Thelon R.
64°
Ennis R.
Clarke R.
Dubawnt Lake
104°
102°

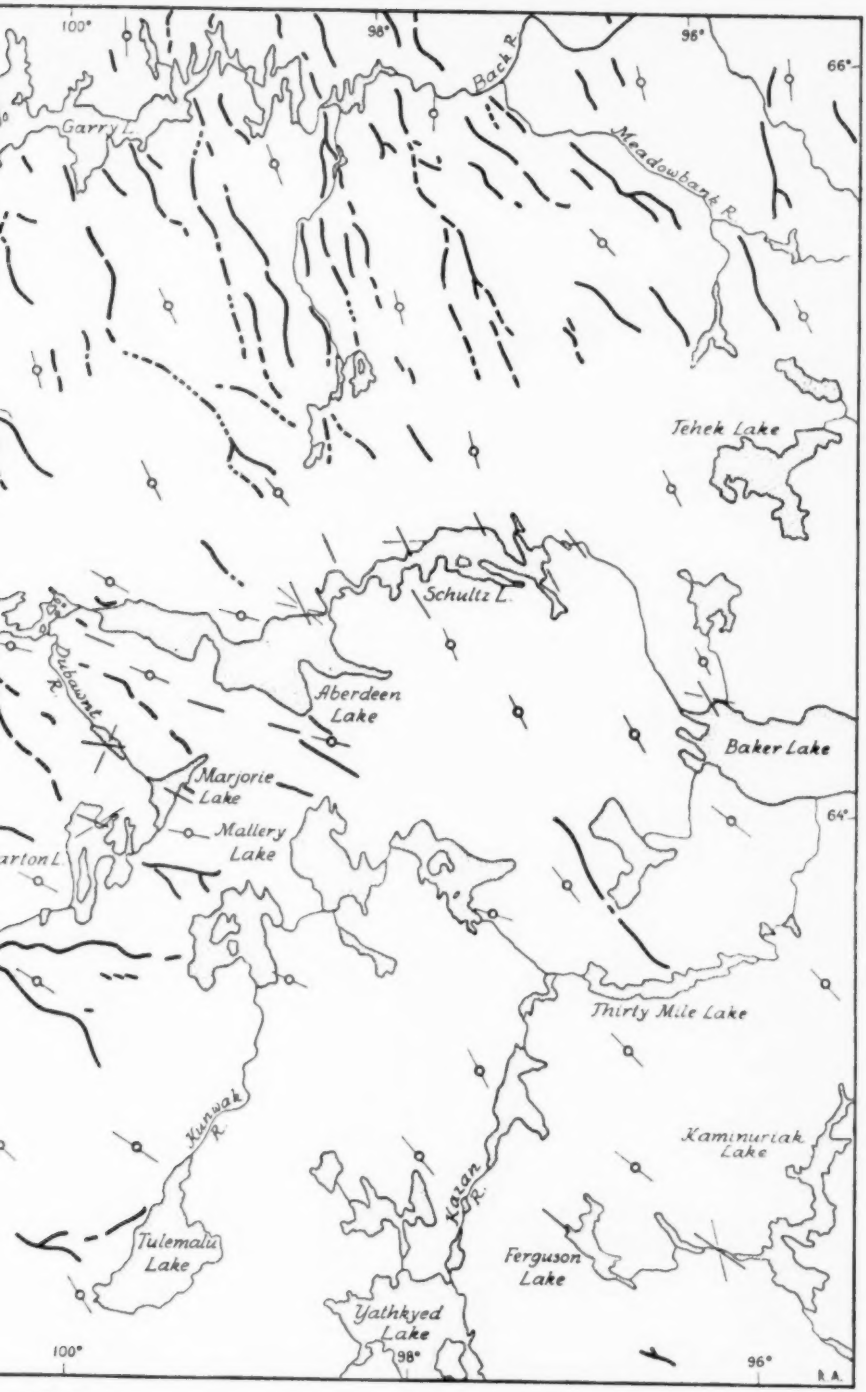

100°
98°
98°
66°
Back R.
Garry L.
Meadowbank R.
Tehek Lake
Schultz L.
Dubawnt R.
Aberdeen Lake
Baker Lake
Marjorie Lake
Mallery Lake
64°
Thirty Mile Lake
Kunwak R.
Kaminuriak Lake
Kazan R.
Tulemalu Lake
Ferguson Lake
Yathkyed Lake
100°
98°
96°

Fig. 2

lag betwen the waning of the ice and the elevation of the land. One result was that the sea submerged many coastal areas, leaving a series of raised strandlines as the water was displaced by the recovery of the land to its present level. At the close of the Ice Age Hudson Bay extended over the low-lying peneplain on its western side. The abandoned beaches in Keewatin are, however, due to causes other than marine submergence. During the waning of the ice sheet, large glacial lakes formed when the normal eastward drainage was blocked by the ice sheet. In southern Canada the extent of the glacial lakes has been traced with considerable accuracy, but in the Northwest Territories, whilst the existence of glacial lakes has been presumed, their limits remain unknown.

The evidence for submergence in the Thelon-Dubawnt Basin includes extensive storm ridges of sand and pebbles, sandspits, cliffs and wave-cut benches in rock and till, all far above the present-day sea and lake levels. J. B. Tyrrell was the first to describe the raised beaches of the region. The highest levels recorded by him were 740 feet above sea level near Dubawnt Lake and 460 feet on Aberdeen Lake. He records terraces farther east on the shores of Schultz Lake and Baker Lake, those near the mouth of the Prince River (at Baker Lake) reaching nearly 400 feet. Although Tyrrell describes the lower strandlines as marine beaches, he recognized the possibility that some of the higher beaches were formed by lakes, for he noted that "Hyper-Dubawnt" Lake had an elevation of 740 feet above sea level (1897, p. 190).

Abandoned storm ridges are nearly continuous on the low hills along the north shore of Baker Lake. They are present up to at least 375 feet—the highest point visited. Wave-cut benches are, however, absent. Raised strandlines are common on both sides of the Thelon gorge between Schultz and Baker lakes, but it was not possible to study them in detail. Many shells of *Saxicava arctica* (Linn.) were found on the surface of the till on the sides of the gorge up to 160 feet above sea level.

On the shores of the three main lakes which form the middle Thelon, abandoned beaches are numerous, but their number, height and character differ between Schultz Lake and the two lakes to the west. Schultz Lake is for the most part surrounded by a prominent raised beach. At its maximum development it has a 200 yard wide surface of sand and gravel. The elevation

at the back of the beach varies between 355 feet and 375 feet (mean, 360 feet) above sea level. When allowance is made for inevitable inaccuracies in altitude measurement by aneroid, and the fact that beaches of varying material and in different exposures are not necessarily formed at the same height in relation to the water surface, these figures are sufficiently close to warrant the assumption that one water level formed all of them.

A thorough survey of the Schultz Lake area failed to reveal any beaches or other evidence of water action above the "360-foot" beach. Below the "360-foot" beach the water level appears to have fallen uniformly to the present lake level. As many as 32 pebble ridges were counted between the "360-foot" beach and the lake, but none could be traced for more than a few hundred yards. The frequent agreement in elevation between the lower ridges around the lake is probably no more than coincidence with the large number of elevations involved.

All the surface deposits below the "360-foot" beach show evidence of water-sorting and rolling, and erratic blocks are absent from rock surfaces. Above the "360-foot" beach, ridges are absent and perched erratics, which in some cases could be moved by hand, are common. The surface deposits are angular and can be differentiated from the deposits below the 360-foot level on sight. If the water surface had been above 360-foot level, the perched blocks would have been dislodged. A similar relation was observed on the east shore of Hudson Bay at Richmond Gulf, where perched erratic blocks are found only above the highest marine beach at 875 feet above sea level (Stanley 1939, p. 1936). In the rear of the beach formed by the present-day Schultz Lake, ice-shove ridges of pebbles and gravel are common, and in some places may be 20 feet high. The "360-foot" beach is peculiar in that it shows no trace of ice-shove ridges. When seen from the air the break in the pattern of the surface deposits at 360 feet around Schultz Lake is very striking. A similar change may be seen from the air photographs in the hilly country around the lower Kazan River, particularly in the vicinity of Thirty Mile Lake. Up to about 350 feet or higher the surface is uniformly smooth, with large numbers of raised beach ridges. Above the highest raised beach, the surface form changes, and unsorted till with a drumlinoid form is dominant.

Sandstone and conglomerate underlie the region around Aberdeen and Beverly lakes. Where these rocks are exposed to the wave action of the present-day lake, as they are at the northeast end of Aberdeen Lake, a wave-cut bench and cliff are commonly present. Any period of constant water level in post-glacial time is, therefore, likely to have left a record in cliffs and benches. Unfortunately, when the matrix is removed from conglomerate by weathering, pebbles remain, which appear to have been water-rolled in the recent past, even when running water was not the erosive agent. A small deposit of pebbles in this region cannot, therefore, be considered positive evidence of water action.

A series of observations was made to determine the elevations of the beaches along twelve traverses in the Beverly Lake-Aberdeen Lake region. The pattern of the beaches was found to change west of Schultz Lake. Whereas around Schultz Lake the highest beach is found at 360 feet, at the east end of Aberdeen Lake evidence of wave action extends to 560 feet. Farther west on the Marjorie Hills, south of the central peninsula of Aberdeen Lake, a wave-cut bench with a low cliff at the rear is found at 740 feet, and small ridges of pebbles are found up to the summit at 800 feet. Beaches are best developed on the hills southeast of Beverly Lake. Wave-cut cliffs were eroded in the fluvio-glacial material, and there are eight distinct benches between 340 feet and 615 feet. Farther east the cliffs and wave-cut benches have been eroded in rock, and so there is less likelihood of finding erosive evidence of very short periods of stability in the water level. Well-developed shorelines are found at 360, 430, 460, 535, 670 and 740 feet above sea level around Aberdeen Lake. Unfortunately, owing to the low relief, the raised strandlines are not continuous for long distances, and it was impossible to trace with certainty the raised beaches from one part of the region to another. For this reason no attempt has been made to correlate these beaches with the raised beaches reported by Tyrrell on the Dubawnt River.

Although west of Schultz Lake the "360-foot" beach ceases to be the upper limit of wave action, it marks a break between two series of beaches. Above 360 feet, low cliffs and wave-cut benches appear, and the vertical interval between beaches increases suddenly. In addition, fossil ice-shove ridges are found at the rear of some beaches above 360 feet.

There can be no certainty that the beaches are of marine or lake origin until fossil shells or other definite evidence is discovered. All the evidence suggests, however, that there was a sudden change in the physiographic forces that produced the beaches when the water level was at 360 feet. The intermittent fall of the water level to 360 feet is more likely to occur in a glacial lake in which progressively lower outlets are uncovered as the ice retreats than in the sea. Below 360 feet the sea receding continuously as the land rises by isostatic adjustment is the more probable beach-forming agency.

Ice-shove ridges form rapidly in suitable exposures around the lakes in Keewatin at the present time. They are, however, normally absent on marine beaches when the tidal range is large. The west coast of Hudson Bay has a tidal range of about 12 feet and ice-shove ridges are absent. It is probable that ridges were not formed around the shores of the enlarged Hudson Bay which existed at the close of the Ice Age.

The presence of ice-shove ridges on the raised beaches above 360 feet may be taken as supporting evidence for the lake origin of the higher beaches. Below 360 feet the absence of ice-shove ridges and wave-cut cliffs in rock, the close spacing and intermittent nature of the beach ridges, and the presence of marine shells in the lower ones support a theory of marine origin.

Beaches are conspicuous features on air photographs from the west of the map area near the confluence of the Thelon and the Clarke rivers. An old strandline has also been reported from a few miles farther west at Dickson Canyon (Clarke, 1940, p. 14). The presence of these beaches and those over 700 feet above sea level in the middle Thelon and Dubawnt Basin suggests that the whole of the map area west of Schultz Lake which is drained by the Thelon and the Dubawnt rivers at the present day was submerged beneath an extensive glacial lake—a lake that even at a conservative estimate must have exceeded 30,000 square miles in area. The outlets by which this lake drained have not yet been discovered, but the several shallow, sandy valleys that lead across the Thelon-Back River watershed and are no longer occupied by rivers may prove to have been overflow channels.

In the absence of field investigations from the Back River, it is difficult to estimate the extent and type of submergence to which it was subjected at the close of the Wisconsin. The sea

apparently entered the middle lakes area of the river, but glacial lakes were either small or never developed. Higher upstream along the Back River (in the extreme west of the map area) small glacial lakes probably existed with outlets to the north.

CONCLUSIONS

Glacial striae and drumlinoids show that there were at least three distinct ice movements in central Keewatin during the Wisconsin glaciation. The earliest ice advance of which unmistakable record is preserved in the area came from the northeast. It was succeeded by a second ice advance that came from eastern Keewatin, or more probably Hudson Bay, and moved across the area in a west-northwesterly direction which became northerly near the Back River. This ice apparently split into two lobes west of Dubawnt Lake, leaving an ice-free area between, in which was preserved evidence of the earlier ice movement. Finally, the central zone of radial outflow shifted toward the south and the eastern third of the map area came under the influence of ice moving from the southeast. None of the three ice movements can be related to the ice centers shown on the map (fig. 1). The closest agreement is with the earliest ice movement that possibly originated near the Back River ice center. Drumlinoids and eskers from southern Keewatin suggest, however, that this ice movement was part of a more extensive flow from a broad ice divide that lay across northern Keewatin. The ice divide was an extension of the main Wisconsin ice sheet located in the Hudson Bay area. This does not necessarily imply that ice centers never existed in Keewatin, but if they did, they were restricted either to the onset of the glaciation or to the close, when the continental ice sheet split into smaller, nearly stagnant ice sheets, in some of which there was undoubtedly local reversal of flow.

The ice lobe which produced the final movement formed a barrier that blocked the natural drainage of the ice-free area to the west. There a glacial lake developed that stretched from Aberdeen Lake to Dickson Canyon, above the junction of the Thelon and Hanbury rivers. The northern shore was probably the Thelon-Back River watershed. The position of the southern shore of the lake is unknown, but the present-day Lake Dubawnt was included in the area. The altitude of the lake when first formed was at least 800 feet above present sea level. As the ice

retreated and thinned, lower outlets were uncovered, and the water fell by stages. By the time the lake level had fallen to 360 feet, the ice had waned sufficiently to enable the sea to invade the area. The sea occupied the basins of the larger modern lakes, and the higher ground between the lakes became islands. Since that time the land has risen and the sea has been gradually displaced to the east until it occupies its present area.

Following the retreat of the post-glacial sea, the action of snow and ice in molding the landscape has been insignificant except on the northwest side of Schultz Lake, where two small valleys not more than 250 feet deep and a mile long may have supported independent glacierets in post-glacial times.

ACKNOWLEDGMENTS

The field work presented in this paper was undertaken during a geographical traverse of part of the Thelon Basin in 1948 for the Geographical Bureau, now the Geographical Branch, Department of Mines and Technical Surveys, Ottawa. The base map for figure 2 was compiled by the author from various sources, including advance map information supplied by the Topographical Survey of Canada, from air photographs supplied by the National Air Photographic Library of Canada, and from a survey made by the author. The glacial striae shown on the map are from observations made by the author along the Thelon River, and by Tyrrell along the Dubawnt and Kazan rivers. The strike of the drumlinoids has been taken from air photographs. The eskers have been plotted from topographic maps, field surveys and from air photographs. Only features that are without question eskers have been mapped as such.

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NOTES ON THE GEOLOGY OF GUADALUPE ISLAND, MEXICO

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ABSTRACT. Geological observations made in 1951 during a short visit to Guadalupe Island, Mexico, indicate the rock sequence to be almost entirely volcanic, with calcic andesite and basalt present. In the limited area studied at the south end of the island, the section is composed of hornblende andesite and cemented tuff. A lithified tuffaceous marl interbedded within the volcanic series contains a marine fauna probably representing the Upper Tertiary or Quaternary. Inner Island, lying off the southern tip of Guadalupe, presents a fine cross-section view of an eroded cinder cone.

INTRODUCTION

DURING the month of August, 1951, the writer and his colleagues, Commander C. N. G. Hendrix, U.S.N., Dr. Edwin L. Hamilton, Navy Electronics Laboratory, San Diego, California, and Mr. Robert Fisher, Scripps Institution of Oceanography, La Jolla, California, participated in a six-day bathymetric survey conducted from the auxiliary schooner *E. W. Scripps* in the waters surrounding Guadalupe Island, Mexico, longitude 118° W., latitude 29° N., about 200 miles southerly from San Diego, California, and 150 miles westerly from the peninsula of Baja California, Mexico (fig. 1). The longitudinal axis of the island lies in a north-south direction extending 20 miles, with the width varying from 3 to 7 miles. Two small islands known as Inner Island and Outer Island, each less than ½ mile in diameter, lie within a 2-mile radius of the southern end of Guadalupe Island.

The topographic aspect of Guadalupe Island is one of bold relief with sea cliffs rising abruptly along most of the coastline to elevations in the 2000- to 3000-foot range (plate 1). Available maps differ in the contour of coastline and topography. The maximum elevation is usually given as 4038 feet and occurs near the north end of the island. Safe deep water anchorages close inshore are limited to Northeast Anchorage and Melpomene Cove (fig. 2) at the south end of the island. Vegetation is sparse, the higher slopes dotted with a scant growth of what

*Contribution from the Scripps Institution of Oceanography, New Series, No. 578.

appears to be Guadalupe pine, oak and cypress as described by Hanna (1925). Intermittent rainfall records indicate an annual precipitation of 3 to 5 inches. Some additional moisture is derived from frequent dense cumulus clouds which shroud the highest elevations during most of the year.

Coincident with the bathymetric survey, landings were made at Melpomene Cove and Northeast Anchorage for the purpose of studying rock relationships. A small boat approach was made

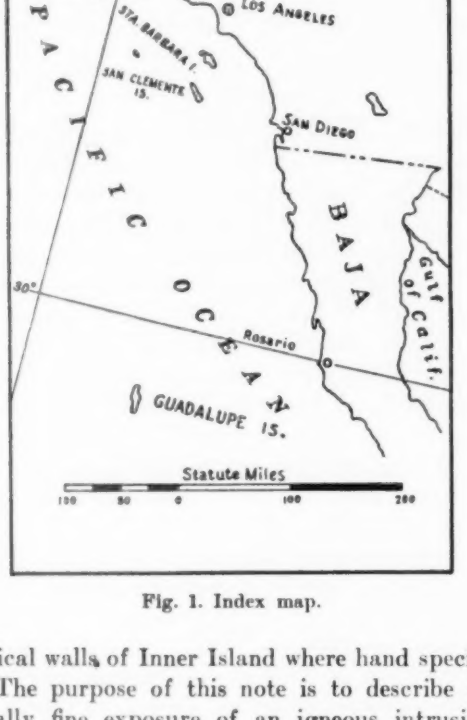

Fig. 1. Index map.

to the vertical walls of Inner Island where hand specimens were obtained. The purpose of this note is to describe and figure the unusually fine exposure of an igneous intrusion on the seaward or west side of Inner Island and to present a short discussion of the rock sequence in the Melpomene Cove area.

ACKNOWLEDGMENTS

The writer is greatly indebted to Dr. Roger Revelle, Director, Scripps Institution of Oceanography, La Jolla, California, and

Plate 1. Southwest coastline.

Plate 2

Fig. 1. Inner Island.

Fig. 2. Inner Island—close-up.

to Dr. Robert S. Dietz, U. S. Navy Electronics Laboratory, San Diego, California, for permission to become a member of the August 1951 expedition to Guadalupe Island and to use data compiled during the cruise. Especial thanks are due Commander C. N. G. Hendrix, U.S.N., Dr. Edwin L. Hamilton, and Mr. Robert Fisher, members of the expedition, for their enthusiastic assistance in many ways. Dr. Charles A. Anderson, U.S.G.S., Prescott, Arizona, kindly made available his field notes taken during a visit to the Island in 1940. The writer is indebted to Professor A. O. Woodford, Department of Geology, Pomona College, Claremont, California, for aid in thin section determinations and helpful criticism of the manuscript. Credit is due Dr. M. L. Natland, Chief Paleontologist, Richfield Oil Corporation, Long Beach, California, for fossil determinations referred to in this report. The aerial photograph showing the southwest coastline of Guadalupe Island was made available through the courtesy of the U. S. Coast and Geodetic Survey.

GEOLOGIC NOTES

During the course of the bathymetric survey numerous close approaches were made to the rugged coastline affording ample opportunity to observe the general distribution of rock types. The principal rock type studied proved to be calcic andesite, usually showing flow structure and occasionally a pahoehoe surface. Observed attitudes of flow structure are usually low, suggesting initial dip and absence of deformation. It is estimated that some 20 per cent of the exposed rocks may be classed as pyroclastic. Tuff and agglomerate varying in color from light pink to buff and gray occur sometimes interbedded with calcic andesite flows, but more frequently as mantle deposits on the most recent andesite surfaces. Here the well-bedded pyroclastics slope away from essentially undissected cinder cones perched along the backbone of the island. In the southern portion outbursts from closely spaced cones have resulted in the coalescence of pyroclastic deposits with resultant discordant bedding. There was no observed indication of deformation in the pyroclastic series.

The sea cliff along the northerly shoreline of Melpomene Cove reveals a volcanic series 200 feet thick with regional 5° southerly dip and a plateau surface. Massive calcic andesite predominates with an aggregate of about 50 feet of tuff present as

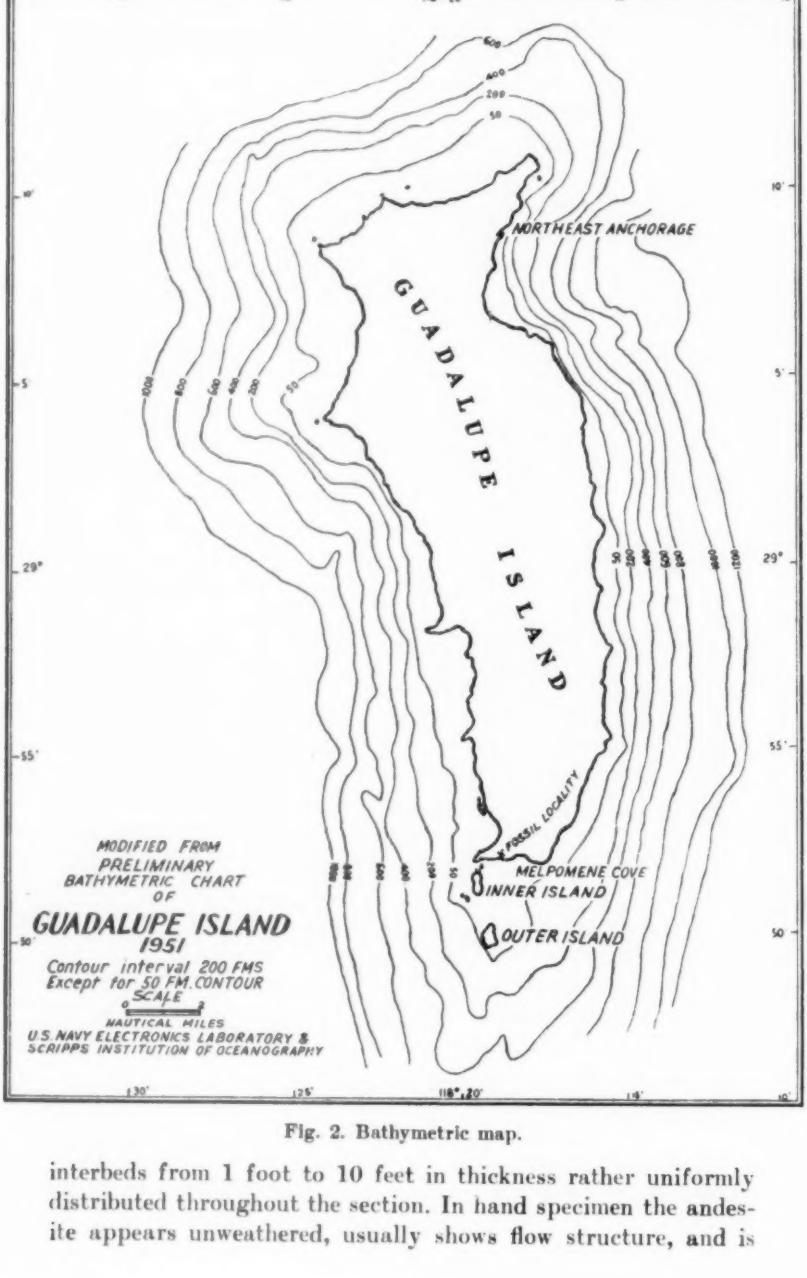

Fig. 2. Bathymetric map.

interbeds from 1 foot to 10 feet in thickness rather uniformly distributed throughout the section. In hand specimen the andesite appears unweathered, usually shows flow structure, and is

often vesicular. Preliminary study of a thin section representative of the vesicular phase indicates a mineral assemblage of hornblende andesite with numerous phenocrysts of labradorite (An 50-55) and basaltic hornblende. The latter has broad, opaque reaction rims with radial structure apparently made up of hematitic material. Magnetite and augite are also present. Numerous vesicles are partially filled with low index colorless minerals, probably including chalcedony. The groundmass is composed mainly of minute lathlike calcic andesine grains. This rock is similar to the calcic andesite of the Glendora volcanics, Los Angeles County, California, as described by Shelton (1946). Some specimens of basalt (?) show common olivine phenocrysts in an aphanitic groundmass.

Samples of the pyroclastics are characteristically buff to tan lithic tuff, often containing lapilli of pumice and vesicular basalt. A thin section from the lithic tuff exposed near the present plateau surfaces shows the main constituent to be glass containing microlites, most of which are plagioclase altering to orange-yellow chlorophaeite. Euhedral grains of basaltic hornblende, olivine, and magnetite occur in that order. Occasional vesicles appear to be filled with chlorophaeite. On the surface of the plateau there is a most remarkable occurrence of residual sand originating from the volcanic landscape. Loose deposits of very fresh, euhedral grains of plagioclase, basaltic hornblende, and olivine up to $\frac{1}{2}$ inch in length lie in depressions where they have been collected by the sweep of the strong prevailing westerly winds. A sample of tuff from Inner Island appears to be palagonitic with numerous minute vesicles.

It has been noted by Anderson, in a personal communication, and also by the writer that certain outcrops of the pyroclastics exhibit excellent stratification and cross-bedding suggestive of water deposition. Mr. Hamilton of our landing party found in these beds what are believed to be the first fossils from Guadalupe Island. A hand specimen of lithified tuffaceous marl from the Melpomene Cove seacliff, about 75 feet above sea level and interbedded within the pyroclastic series, yielded a marine fauna which has been identified by Dr. M. L. Natland. The fossil material was collected along a path skirting the seacliff about 500 feet easterly from the weather station maintained by the Mexican government. Dr. Natland comments: "The sample of lithified tuffaceous marl interbedded with volcanics on Guadalupe Island contains an unidentifiable, small (maximum dia-

meter 1.00 mm.) unornamented, pearly-lustered gastropod. Many foraminiferal specimens similar to *Anomalina schmitti* were dislodged intact from the rock. In general they are thicker and have a larger umbo than the Southern California Recent and Tertiary specimens. A thin section of the material contained cross sections of *Discorbis cf. rosaceus*, *Miliolidae*, Echinoid spines, and fish scales. Until more material is collected from the area no positive age assignment is possible other than that it is probably Upper Tertiary or Quaternary. The fauna indicates a shallow water marine environment."

Similar andesite, basalt, and pyroclastic rocks widely exposed throughout the southern portion of the peninsula of Lower California have been designated Quaternary to Miocene by Beal (1948, pp. 74-77 and 84-85), Anderson (1950, pp. 11-14), and others.

Inner Island, located about ½ mile south of the southerly tip of Guadalupe Island, rises to an elevation of 600 feet, and is about 1500 feet in width at sea level. Viewed from the east, Inner Island appears to be entirely composed of low-dipping, tan-colored, lithic tuff with sporadic angular blocks of basic flow rock.

The western seacliff of Inner Island (plate 2, fig. 1)presents a "textbook illustration" of the phenomena associated with igneous activity along a volcanic conduit. Apparently the most recent epoch of volcanic activity included the rise of basic magma through a central conduit about 20 feet in diameter. The dikes (plate 2, fig. 2) visible on the right side of the central neck are probably contemporaneous. A baked tuff zone, brick-red in color and approaching 25 feet in width, is present along the margins of the dikes and central conduit.

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COMMUNICATION

Professor I. S. Allison's paper "Dating of Pluvial Lakes in the Great Basin" (this Journal, December, 1952, pp. 907-909) contains a serious error. The radiocarbon samples C609 and C610 ("C" stands for University of Chicago) from Danger Cave near Wendover, Utah, were taken, *not* at the Stansbury level 330 feet above Great Salt Lake, but at about 110 feet above the lake. The altitude of the samples was 4312 feet (letter of June 23, 1951, from Professor Jesse D. Jennings, University of Utah), while those of the Stansbury shoreline and of the zero of Great Salt Lake lake shore gauge are 4530 and 4203 feet, respectively.

Therefore the radiocarbon dates from Danger Cave (sample C609: 11,450 years; C610: 11,150) and for the Mankato glacial culmination (samples C308, C365, C366, C536 and C537 from Two Creeks, Wisconsin, averaging 11,400 years, making the Mankato maximum about 11,000 years) make a lake, standing less than 100 feet above Great Salt Lake, a correlative of the Mankato maximum. Or, if the Stansbury or a higher shore corresponded to the Mankato maximum, its radiocarbon age (11,000 years) would be lower than that (11,150 or 11,450 years) of a 220 or more feet lower, later lake. Since both consequences are unreasonable, at least one of the two sets of radiocarbon dates must be incorrect. Rather than being a correlative of the Mankato maximum, the Stansbury shore, which stands 270 or more feet below the Provo shoreline, may correspond to the Sioux Lookout-Pembroke or the Cochrane stages. This is in accord with the recent studies of Roger Morrison and Harold Bissell.

Ernst Antevs

The Corral
Globe, Arizona

REPLY

I am grateful to Dr. Antevs for the correction, just as I am sorry to have been misled on the correlation of the Danger Cave deposits with the Stansbury Beach. On account of the difference in their levels Danger Cave clearly is later. So I retract the correlation of the Stansbury phase of Lake Bonneville with

the Mankato glacial substage, but I see no need to withdraw the correlation of the Danger Cave deposits and the ZX Red Barn Beach (Oregon) with the Mankato.

Contrary to Dr. Antevs' view that a pluvial lake of Two Creeks-Mankato age standing only 110 feet above the present Great Salt Lake is unreasonable, I think we should accept the radiocarbon dates, at least until they have been proved to be wrong, and that we should adjust our stratigraphy accordingly.

If the radiocarbon dates are dependable, then the Stansbury Beach, as well as the Bonneville and Provo shorelines, also is pre-Mankato, and the entire pluvial lake history is even longer still than previously thought—the purport of my original article. I regret to differ with Dr. Antevs at this point.

Ira S. Allison

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REVIEWS

The Aurorae; by L. HARANG. The International Astrophysics Series, Vol. 1. Pp. x, 166; 152 figs. New York, 1951 (John Wiley & Sons, Inc., $4.50).—The emphasis of this monograph throughout is on the presentation of observational data and the description of techniques developed by the Norwegian school of students of the aurorae. This partiality has been carried rather far. Why should the names of Gaertlein and Meinel, for instance, be absent from the index of authors? Likewise, aurorae theories not favored by the Norwegian school are largely disregarded. This omission is more serious, because Störmer's views on the excitation of aurorae are now regarded by most theorists as of historical interest only.

The literature of astrophysics is notoriously deficient in books. Hence the project of this international series will be generally acclaimed. The layout of the first sample is pleasing, and the large type chosen will be welcomed by all who regret the recent change to smaller type forced upon the Astrophysical Journal by reasons of economy. Unfortunately, the typography of the mathematical equations is rather unsatisfactory. Moreover, there are numerous misprints in the formulae. The reproduction of diagrams and line drawings is excellent, but all illustrations in halftone suffer from lack of detail due to unsuitable paper. One cannot but regret that the aurorae photographs are scattered through the text, instead of being reproduced on high-gloss paper. RUPERT WILDT

Geologic Guidebook of the San Francisco Bay Counties—History, Landscape, Geology, Fossils, Minerals, Industry, and Routes to Travel; prepared under the direction of OLAF P. JENKINS. California Department of Natural Resources, Division of Mines, Bull. 154. Pp. 392. San Francisco, 1951 ($2.50).—This admirable volume is the product of the cooperation of twenty-eight authorities. It covers the twelve counties that surround San Francisco Bay, an area in which 3,000,000 people live.

The book consists of seven parts. *PART I,* begins with the "Opening of the Golden Gate" and gives the historical background of the region.

It commences with the early sea voyages of exploration which began with Cabrillo in 1542, recounts the belated, unexpected discovery of San Francisco Bay in 1769 by the land expedition of Portola, and sketches the subsequent history up to the time of the great gold rush. Other papers deal with the origin of the place names, with accounts of the original Indian inhabitants, with the adobe houses in the Bay region, and with the old lime kilns near Olema in Marin County.

PART II, entitled "History of the Landscape," comprises two papers: one dealing with the geologic history of San Francisco Bay by G. D. Louderback, in which the idea is advanced that the Bay began first to develop during the rise of sea level during the third Interglacial; and the other, "Development of the Landscape of the San Francisco Bay Counties," by A. D. Howard outlines the evolution of the landscapes of the twelve counties surrounding the Bay. These papers, like most of the others in the book, are supported by ample bibliographies.

We come now to a much longer section, *PART III*, "Geological History." The history of geologic investigations in the Bay region is given by V. L. VanderHoof. The geology of the region is fully but succinctly presented by N. L. Taliaferro in an account that will serve as a convenient summary of our present knowledge of the Central Coast Ranges. It would doubtless have heightened the interest of this section to geologists to have mentioned that the micropaleontologists are finding Late Cretaceous foraminifera in a disconcerting number of localities in alleged Franciscan rocks of supposed Jurassic age. The history of the earthquakes is given by Perry Byerly.

"Prehistoric Life" comprises *PART IV*, in which R. A. Stirton describes the prehistoric land animals, L. G. Hertlein the invertebrate fossils and the fossiliferous localities, and R. W. Chaney the prehistoric forests.

PART V consists of fourteen separate articles on the mineral industry of the Bay region. It is a surprisingly highly diversified industry. E. A. Bailey contributes a remarkably interesting account of the famous New Almaden quicksilver mine.

In *PART VI* the surface water supplies are described by R. L. Wing.

PART VII is called "Places To Go and Routes To Go." The geology of the Farallon Islands, small rocky islets 30 miles west of the Golden Gate, is described by G. Dallas Hanna.

The more interesting minerals of the Bay region are listed by R. A. Crippen, Jr., and the more notable localities at which they occur are briefly mentioned. In "Highways and Byways of Particular Geologic Interest," O. E. Bowen, Jr., gives detailed road logs of the principal highways, a very helpful feature for those who desire to examine the geology of the region for themselves.

Finally, a Glossary and an Index have been added. In addition to its numerous other excellences, the volume is remarkably well illustrated. The authors and Dr. Olaf P. Jenkins, Chief of the Division of Mines, under whose direction the volume was prepared deserve warm congratulations. This book sets a high standard that similar accounts of other regions will do well to emulate.

ADOLPH KNOPF

Révision de la Faune des Mammifères Oligocènes d'Auvergne et du Velay; by R. LAVOCAT. Pp. 153; 26 plates, 1 map. Paris, 1951 (Editions "Sciences et Avenir").—The Oligocene (Sannoisian-Stampian) faunas of Auvergne and the Velay, France, were described for the most part in the 1840's and 1850's. Many later publications have discussed parts of these faunas and have added new elements. Such work has, however, been partial and somewhat haphazard. It has been quite impossible to obtain a really accurate overall view of these classical faunas, which bear on many of the most important problems of historical geology, paleogeography, and mammalian phylogeny. The publication of a thorough, careful revision by the Abbé Lavocat is therefore an event of major importance for all who are interested in such problems.

The faunas as a whole include, as revised, 86 species, each of which is adequately described and illustrated. Four genera and eleven species are new. It would be out of place here to discuss the abundant details of the revision, and it suffices to call the attention of students of the Oligocene and its mammals to this rich source of basic information.

The systematic contribution of most novel importance is the description and discussion of the Theridomyidae. This family comprises a compact group of late Eocene and Oligocene European rodents. Their affinities have been widely discussed and bitterly disputed. Most persistent has been the claim that they are related to the older native rodents (so-called "hystricomorphs") of South America – a view that raises fundamental questions about paleogeography as well as phylogeny. Lavocat establishes beyond much doubt that no such special relationship exists. The Theridomyidae seem to be an independent, self-contained offshoot from the most primitive and widespread Eocene rodent stocks, related neither to the South American rodents nor to any later Old World lines.

Geographic relationships and origins of the faunas are discussed interestingly and in some detail but rather inconclusively. On the whole, the new data seem to agree sufficiently with the long-current view of connection between North America and Europe through central and northern Asia in the early Oligocene. However, Lavocat also has recourse to a hypothesis of peculiarly intricate convergence to explain the common occurrence in Europe and North America of some carnivore genera. To the reviewer, the hypothesis seems next to impossible genetically and quite unnecessary paleogeographically.

The numerous local faunas involved are nowhere formally listed. This serious omission makes it practically impossible for the reader to grasp their relationships or the faunal sequence within the long span of time covered by them. The printing and proofreading are poor and detract from what is in most respects a publication of highest value.

G. G. SIMPSON

The Elements of Genetics; by C. D. Darlington and K. Mather. Pp. 446; 88 figs., 31 tables. New York, 1949 (The Macmillan Company, $5.25).—When one picks up a book with *The Elements of Genetics* handsomely imprinted on its spine, he is entitled, at the very least, to expect that the basic principles of the subject concerned will be lucidly presented with a clean distinction between factual data and hypothesis. Although he does not expect to extract all the subtleties or complexities of the subject from such a work, it should provide him with a balanced and reasonably objective view of the major problems of the field even if it be somewhat dull reading. In the case of Darlington and Mather's *The Elements of Genetics* these expectations are rather completely upset, for here is a work which is fascinating in many respects, at once stimulating and exasperating to the specialist, and misleading if not downright dangerous for the novice. The central position of genetics in biological theory gives it the greatest significance in the unification and generalization of biological principles. It thus encourages speculation and provisional theorizing over a great range of biological phenomena. In their attempt to cover this range with the implications of genetic theory the authors are aware that they have indulged extensively in speculation (and not for the first time in their writings!) and so warn the reader in an ingenious preface. It is not the colossal audacity of the "Dangerous Speculations" in new theories which constitute the danger of the book, since they are almost always evident or so labelled. It is rather that so much that is presented as established "Laws of Nature" consists of theoretical improvisations, certain of which have been shown to be either without adequate experimental verification, or otherwise untenable. The reader must be wary of such things as reciprocal chiasmata in the male of *Drosophila* (presented as a "Law of Nature" in the form of a diagram rather than as unverified hypothesis), of "nucleic acid charges" of chromosomes, of "molecular coiling," of the misdivision of centromeres, of the "activity of heterochromatin," and of the prevalence of plasmagenes. While the genetical reader will have his doubting glasses on from the beginning, the non-specialist reader will have a harder time discerning the fact among the fiction, since the transition from "Laws of Nature" (which are sometimes spurious) to the new theorizing is a gradual one. Furthermore there are some serious omissions or oversights as indicated below.

On the other side of the picture the attempt to provide a panoramic view of genetical principles and their bearing on major biological problems is admirable, even though not completely successful. The organization of the treatment by levels: individuals, cells, and populations, is both logical and convenient, something more than a hundred pages being devoted to the first which is concerned more

or less with the classical genetics of individuals. The second section of about seventy-five pages, entitled "Cells," is an expansion of the Darlingtonian synthesis of "heredity, development and infection," while the third part of the book, "Populations," deals with certain phases of genetics in relation to evolution, with emphasis on the "evolution of heredity." Much of the material in these two sections is of the greatest interest to those concerned with the problems of development and evolution. However, the failure to present even the elements of the statistical genetics of populations and their implications for evolution, as so beautifully developed by Sewell Wright and others, is a grave deficiency in a work more than a third of which is sub-titled "Populations." This cannot be due to an aversion to mathematical formulation, for the authors use it extensively in the treatment of continuous variation and one of them has written several books of biometrical character. Yet these unexpounded principles of population genetics underlie the more significant portions of their discussion of human diversity and evolution! Another striking omission is encountered in connection with mutation. No systematic account is given of spontaneous or induced mutation and the name of the most active present-day student of the process of mutation is not to be found in the text or index. In a book differently titled one might overlook certain of these shortcomings. This is not "The Elements of Genetics"; it might be more appropriately entitled "Speculatio Genetica."

The book is well documented, there being reference lists at the end of each chapter together with an appendix of genetical books published in the English language. Other appendices comprise an extensive glossary and an account of the symbols employed.

D. F. POULSON

Genes, Plants, and People, Essays on Genetics 1929-1948; by C. D. DARLINGTON and K. MATHER. Pp. xxi, 187; 13 figs. Philadelphia, 1950 (The Blakiston Company, $4.00).—In contrast to *The Elements of Genetics* by the same authors reviewed above, this volume represents the reprinting of a series of essays which appeared between the years 1929 and 1948 in "Nature" and a few other British periodicals. In certain of them can be discerned the germs of the larger book. Running through most of them is the theme of genetics as the unifier of modern biology. The essays range in subject from the "Early Hybridizers" and the "Origins of Genetics" through various aspects of twentieth-century cytology and genetics to an account of the "New Soviet Genetics." All are interesting and stimulating reading and, in some cases, highly speculative. Best known of the essays is Darlington's "Heredity, Development and Infection" in which he put forward his conception of the relations of plasma-genes and viruses to the genetic system. Along

with his "Chromosome Chemistry and Gene Action," it is clearly the most speculative of the essays, but in both cases the speculation is fairly readily distinguishable from the fact, and the presentation is brilliant. The essays by Mather are also notable, although several deal with rather special subjects. His "Significance of Nuclear Change in Differentiation" provides a simple introduction to a fascinating field.

The reprinting of these essays in book form is a service, especially to the younger student of biology and the general reader to whom they would otherwise be rather inaccessible, as well as to biologists in general.

D. F. POULSON

Grasses of Wisconsin: The Taxonomy, Ecology, and Distribution of the Gramineae Growing in the State without Cultivation; by NORMAN C. FASSETT (with an essay, *The Vegetation of Wisconsin;* by JOHN T. CURTIS). Pp. 173; 353 figs., 182 maps. Madison, Wisconsin, 1951 (The University of Wisconsin Press, $3.00).—This work, which treats all the grasses found growing without cultivation in the state of Wisconsin, is more than a check list—it is a flora complete with keys, accurate range maps, and excellent illustrations. Practically all the figures are reproduced from Hitchcock's Manual, and the range maps are based upon actual collections examined by the author.

The structure of grasses is quite different from that of other flowering plants and for this reason it is necessary to use a rather specialized terminology. In the introduction there is a discussion of grass morphology, written in a language that even non-botanists can readily understand. This clearly written section, along with the frequent references to the figures, should give the uninitiated a feeling of confidence as he begins his determinations. An adequate glossary is also included. It would have been preferable, perhaps, if the plate showing the structure of grasses (figs. 353-356) had been placed with the introduction rather than near the end of the book. The keys are simply written and there seems to have been a conscious avoidance of technical language except insofar as it is necessary for preciseness.

Following a procedure which is reminiscent of Deam's Flora of Indiana, Dr. Fassett has made no attempt to include complete descriptions. Instead, there are notes regarding the habitat, the range, and often some characteristic feature of the taxon under discussion.

The author states that in most cases the names employed are the same as those in Hitchcock's Manual. In some cases, particularly in the genus *Panicum,* Dr. Fassett's treatment is much more con-

servative than that of Hitchcock and there is probably much to be said in favor of this conservatism.

Throughout the book, whenever the author's treatment differs from that of Hitchcock and Chase, there is usually ample discussion, complete with references to the pertinent literature. A few puzzles, however, are to be found as, for example, in the genus *Lolium* (p. 41). Dr. Fassett lists one species, *L. perenne*, stating that the florets may be awned or awnless and also that they may vary in size. On page 128 the illustrations show spikes of the two forms, the spike with the awned florets being labelled *L. perenne* and that with the awnless, *L. multiflorum*. These illustrations are taken from Hitchcock's Manual but the names have been reversed. The problem is further confused since Fassett's text implies that in Wisconsin there is but one species (*L. perenne*).

This compact grass flora should be useful, not only to those interested in Wisconsin's grasses, but also to other students of the Gramineae, particularly those in the Northeastern United States. Fortunately it is small enough to be carried in the pocket and can thus serve as a field guide. The book should also be an appropriate text for courses in Agrostology. JOHN R. REEDER

Die natürlichen Grundlagen des Pflanzenertrags in Mitteleuropa; by PAUL FILZER. Pp. viii, 198; 25 figs., 35 tables, 3 maps. Stuttgart, 1951. (E. Schweizerbart'sche Verlagsbuchhandlung, DM. 17.60).—This book is a study of the natural bases of plant yield in Central Europe, thoroughly conducted and of considerable interest to workers in the fields of ecology, plant geography, agriculture, silviculture, and plant economy. A general section deals with the comparative merits of the analytical and the synthetic-organismic research methods in ecology, and with the interrelationships between climate, soil and vegetation. There follow sections on methods and results in plant-yield research, production factors as affected by precipitation, temperature, and biological conditions, and on general applications. Many important data have been incorporated in the text and are given in table form. There are a bibliography and an index. The volume is well written and thoroughly modern in its organismic and holistic approach to theoretical and practical problems in this important field. ROBERT BLOCH

PUBLICATIONS RECENTLY RECEIVED

U.S. Geological Survey Water-Supply Papers, as follows: 1000, Geology and Ground-Water Resources of the Santa Maria Valley Area, California; by G. F. Worts, Jr. ($1.75). 1111, Surface Water Supply of the United States, 1948, Part 1, North Atlantic Slope Basins; C. G. Paulsen, Director ($1.75). 1106, Public Water Supplies in Western Texas; by W. L. Broadhurst, R. W. Sundstrom, and D. E. Weaver ($0.50). 1107, Geology and Water Resources of the Santa Ynez River Basin, Santa Barbara County, California; by J. E. Upson and H. G. Thomasson, Jr. ($1.00). 1108, Geology and Ground-Water Resources of the South-Coast Basins of Santa Barbara County, California; by J. E. Upson ($1.50). 1110-B, Ground Water in the Cuyama Valley, California; by J. E. Upson and G. F. Worts, Jr. ($0.65). 1134-A, Flood of August 4-5, 1943 in Central West Virginia; by H. M. Erskine ($0.40). 1142, Surface Water Supply of the United States, 1949, Part 2, South Atlantic Slope and Eastern Gulf of Mexico Basins ($1.50). 1145, Part 5, Hudson Bay and Upper Mississippi River Basin ($1.25). 1146, Part 6, Missouri River Basin ($1.75). 1147, Part 7, Lower Mississippi River Basin ($1.00). 1150, Part 10, The Great Basin ($0.50). 1154, Part 14, Pacific Slope Basins in Oregon and Lower Columbia River Basin ($0.70); C. G. Paulsen, Director. Washington, 1951.

Tidal Datum Planes; by H. A. Marmer. U.S. Coast and Geodetic Survey Special Pub. no. 135, revised edition. Washington, 1951 (Government Printing Office, $0.60).

Geologic Guidebook of the San Francisco Bay Counties; prepared under the direction of Olaf P. Jenkins. California Division of Mines Bulletin 154. San Francisco, Calif., 1951 ($2.50).

The Lakes of Minnesota, Their Origin and Classication; by James H. Zumberge. Minnesota Geological Survey Bulletin 35. Minneapolis, 1952. (University of Minnesota Press).

Pathology in Forest Practice, 2d ed.; by Dow V. Baxter. New York, 1952 (John Wiley & Sons, Inc., $7.50).

Oil Shale in Kansas; by Russell T. Runnels, and others. State Geological Survey of Kansas, Bulletin 96, Part 3. Lawrence, Kansas, 1952.

Report of the Committee on the Measurement of Geologic Time, 1950-51. Washington, 1952 (Div. of Geology & Geography, National Research Council, $1.00).

Poultry Breeding, 3d ed.; by Morley A. Jull. New York, 1952 (John Wiley & Sons, Inc., $6.00).

Color in Business, Science, and Industry; by Deane B. Judd. New York, 1952 (John Wiley & Sons, Inc., $6.50).

Dana's Manual of Mineralogy, 16th ed.; revised by Cornelius S. Hurlbut, Jr. New York, 1952 (John Wiley & Sons, Inc., $6.00).

Water, A Study of its Properties, its Constitution, its Circulation on the Earth, and its Utilization by Man; by Sir Cryil S. Fox. New York, 1952 (Philosophical Library, Inc., $8.75).

Prelude to History, A Study of Human Origins and Palaeolithic Savagery; by Adrian Coates. New York, 1952 (Philosophical Library, Inc., $4.75).

Parasitism and Symbiosis; by Maurice Caullery. New York and London, 1952 (The Macmillan Company and Sidgwick and Jackson, Limited, $5.50).

The Atmospheres of the Earth and Planets, revised ed.; edited by Gerard P. Kuiper. Chicago, 1952 (University of Chicago Press, $8.50).

Mechanics and Properties of Matter; by Reginald J. Stephenson. New York, 1952 (John Wiley & Sons, Inc., $6.00).

Native Orchids of North America; by Donovan S. Correll. Waltham, Mass., and New York, 1950 (The Chronica Botanica Co., and Stechert-Hafner. Inc., $7.50).

Analytical Mechanics for Engineers, 4th ed.; by Fred B. Seely and Newton E. Ensign. New York and London, 1952 (John Wiley & Sons, Inc., and Chapman and Hall Limited, $5.50).

Geography in the Making; by John K. Wright. New York, 1952 (American Geographical Society, $5.00).

Astrographic Catalogue, 1900·0, Perth Section, Dec.—31° to 41°. From Photographs taken at the Perth Observatory, Western Australia and Measured at the Royal Observatory, Edinburgh, Vol. III, Measures of Rectangular Co-ordinates and Diameters of 68.284 Star Images on plates with centres in Dec.—38°. Paris, 1952 (International Astronomical Union).

Observations made with the Cookson Floating Zenith Telescope in the Years 1927-1936 at the Royal Observatory, Greenwich, and the Determinations of the Variation of Latitude and the Constant of Nutation from Observations in the Years 1911-1936. London, 1939 (His Majesty's Stationery Office, 15*s*).

Proceedings of the London Conference on Optical Instruments, 1950. New York, 1952 (John Wiley & Sons, Inc., $7.00).

Elemente der Philosophie und der Mathematik; by Andreas Speiser. Basel, Switzerland, 1952 (Verlag Birkhäuser, bound Fr. 11.45).

Chemische Analyse der Gesteine und Silikatischen Mineralien; by J. Jakob. Basel, Switzerland, 1952 (Verlag Birkäuser).

The Nature of Some of our Physical Concepts; by P. W. Bridgman. New York, 1952 (Philosophical Library, $2.75).

Introduction to Geology, 3d ed. ; by E. B. Branson and W. A. Tarr (Revised by C. C. Branson and W. D. Keller). New York, 1952 (McGraw-Hill Book Company, $5.50).

Review of Pharmacy, 7th ed.; by George W. Fiero. New York, 1952 (John Wiley & Sons, Inc., $3.25).

Smithsonian Logarithmic Tables; by G. W. Spenceley, R. M. Spenceley, and E. R. Epperson. Smithsonian Miscellaneous Collections, Vol. 118. Washington, 1952 (Smithsonian Institution, $4.50).

Dead Cities and Forgotten Tribes; by Gorden Cooper. New York, 1952 (Philosophical Library, $4.75).

General Biology, 3d ed.; by Perry D. Strausbaugh and Bernal R. Weimer. New York, 1952 (John Wiley & Sons, Inc., $6.00).

General Chemistry, 6th ed.; by H. G. Deming. New York, 1952 (John Wiley & Sons, Inc., $5.75).

Elementary Analysis; by Kenneth O. May. New York, 1952 (John Wiley & Sons, Inc., $5.00).

Pleistocene Geology of the Danville Region; by H. E. Eveland. State Geological Survey of Illinois Report of Investigations 159. Urbana, 1952.

Geology of the Fluorspar Deposits of Illinois; by J. Marvin Weller and others. State Geological Survey of Illinois Bull. 76. Urbana, 1952.

Minor Elements in Kansas Salt; by R. T. Runnels and others. State Geological Survey of Kansas, Bull. 96, part 4. Lawrence, 1952.

The Physical Chemistry of Surface Films; by W. D. Harkins. New York, 1952 (Reinhold Publishing Corp., $10.00).

A Course in College Chemistry; by V. R. Damerell. New York, 1952 (The Macmillan Company, $5.50).

ERRATA

In the paper by Arthur J. Boucot entitled "Life and Death Assemblages among Fossils" (January 1953) the fourth line of the Abstract (p. 24), "biocoenosis . . ." should be deleted.

The author has asked us to point out the following errors:

Figures 1-5 (p. 28) should have been arranged as shown below:

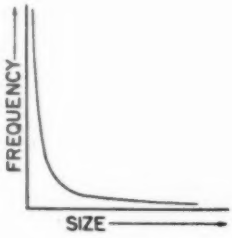

Fig. 1.
Normal survivorship curve.

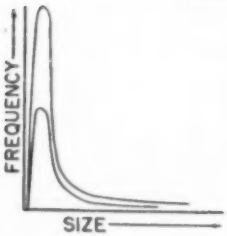

Fig. 2.
Mortality curves for two sets with differing initial population densities and unvarying mortality rate.

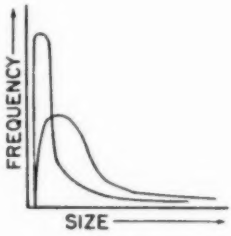

Fig. 3.
Mortality curves for sets with differing mortality rates.

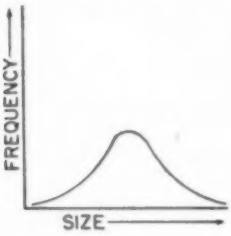

Fig. 4.
Bell-shaped normal distribution curve.

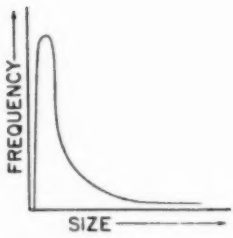

Fig. 5.
Predicted size-frequency distribution for a life assemblage.

On page 39, line 3, a "9" should be substituted for the "6"; line 9, a "7" should be substituted for the "8."

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